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LARP HQM01 Test Summary

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Content:

1. Introduction

HQM01 is a 1-m long Nb_3Sn coil assembled and tested in a test structure designed to provide a quadrupole magnetic field environment (magnetic mirror structure). The coil 12 of HQ series was fabricated as part of the US LHC accelerator research program (LARP) developing a large bore (120 mm) interaction region quadrupoles for the LHC luminosity upgrade [1], [2].

The two layer coil in HQM01 uses a 35-strand Rutherford cable with a 25-μm thick Stainless Steel core and S2-glass sleeve insulation. 0.8-mm diameter RRP strand of a 54/61 stack cross-section was produced by Oxford Superconductor Technologies, Inc. [3]. The azimuthal size of the reaction and impregnation cavity for coil 12 was increased by 1000 μm on each side with respect to the nominal value providing about 3% of additional space per turn. This was done to avoid excessive compaction and related azimuthal pressure on the coil during reaction.

The magnet was tested in the Vertical Magnet Test Facility (VMTF) at Fermilab [4]. The test plan included quench training and ramp rate dependence study in boiling liquid helium at 4.6 K and at lower temperatures 2.2-2.5 K. Protection heater study and high MIITs study were performed at 4.6 K.

HQM01 magnet was installed into the VMTF dewar and it was electrically checked by May 6th, 2011. The VMTF dewar was filled with liquid helium on May 9th. The test was started on May 10th and was completed on June 3rd. Finally, the HQM01 magnet was removed from the VMTF dewar on June 10th, 2011.

2. HQM01 Structure and Instrumentation

A quadrupole magnetic mirror structure was developed at Fermilab to provide an efficient and fast way to test and optimize Nb_3Sn quadrupole coils. This structure allows testing individual coils under operating conditions similar to that of a real magnet, thus reducing the turnaround time of coil fabrication and evaluation, as well as material and labor costs. Previously the TQ quadrupole coils were successfully tested in a mirror structure for study of the effect of pre-stress on the Nb_3Sn coil performance [5].

HQM01 is the first HQ coil tested in a mirror structure (see Fig. 1, left). This structure is similar to the structure used for TQ coils [5], using the iron yoke, iron mirror blocks and bolt-on skin. Preload is applied by a series of shims placed radially and azimuthally on the coil, and to the upper surface of the side "ears" on the mirror block. The magnetic flux distribution in HQM01 cross section is shown in Fig. 1, right.

HQ coil 12 is equipped with 4 protection heaters, 2 on each coil layer (see Fig. 2). Protection heaters were made of stainless steel with 6.0-6.5 Ohm resistance at room temperature. All heater signals were brought to the distribution box at VMTF where the final connections were made to the heater firing units (HFU).

Voltage tap system in HQM01 covers the inner and outer coil layers, pole turn, multi-turn and splice sections (see Fig. 3). There are 10 voltage taps on the inner layer and 10 voltage taps on the outer layer. Only one voltage tap (**A**10) was found floating after first few quenches.

21 strain gauges (SG) were installed on shell, coil and bullets for monitoring mechanical strain and calculating coil stresses during the magnet construction and testing. There are only 2 SG on the titanium pole pieces which consist of active and temperature-compensating gauges connected into a full-bridge circuit. All other gauges are single gauges installed on shell and bullets. Temperature-compensating gauges were mounted on upper and lower half-skins and on lead-end and return-end bullets.

In addition to the standard set of dewar temperature sensors, 2 additional resistive temperature devices (RTD) were mounted at the top and the bottom of the outer magnet skin (*Cernox cx43233* and *cx43235* sensors respectively).

Since the mirror structure does not have room for a magnetic warm bore, flat printed circuit boards (PCB) were used to localize quenches. 4 cm boards were distributed evenly with 30 cm spacing. More details on the location of PCBs are presented in Section 6.

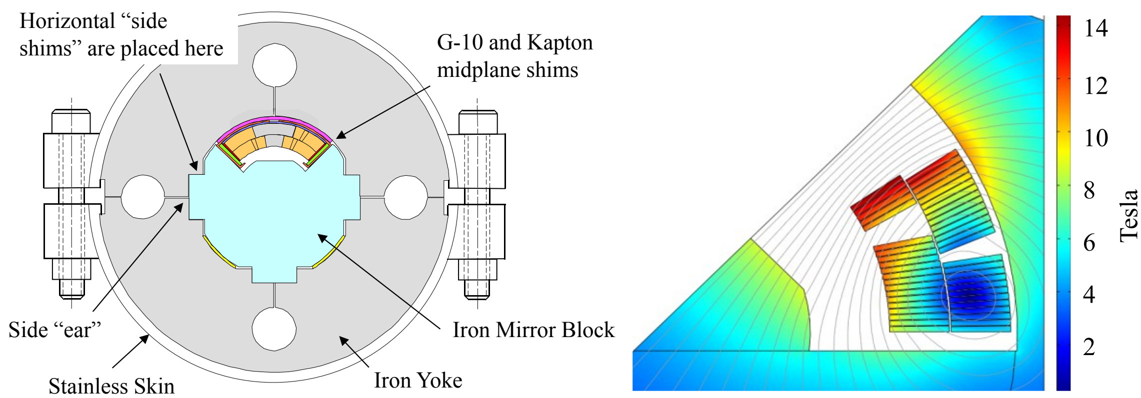

Fig. 1 HQ mirror structure (left) and HQ mirror cross section with flux distribution at 20 kA (right). Peak field at inner pole is 14.9T.

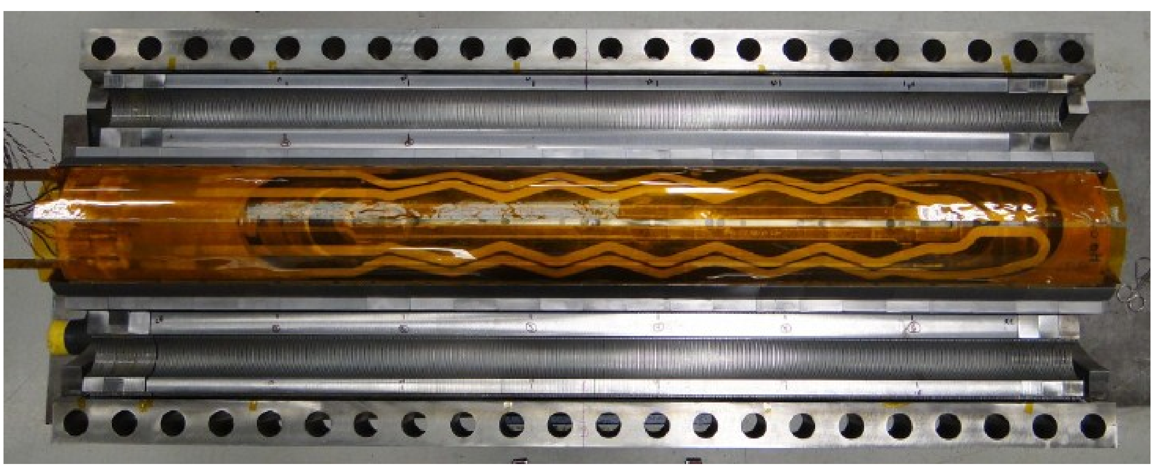

Fig. 2 HQ coil 12 in a mirror structure.

Both VME- and FPGA-based quench detection systems were used in this test. Current-dependent thresholds were used for half-coil signals in both systems. The 1st half-coil signal is formed by the inner coil layer and the 2nd half-coil signal by the outer coil layer.

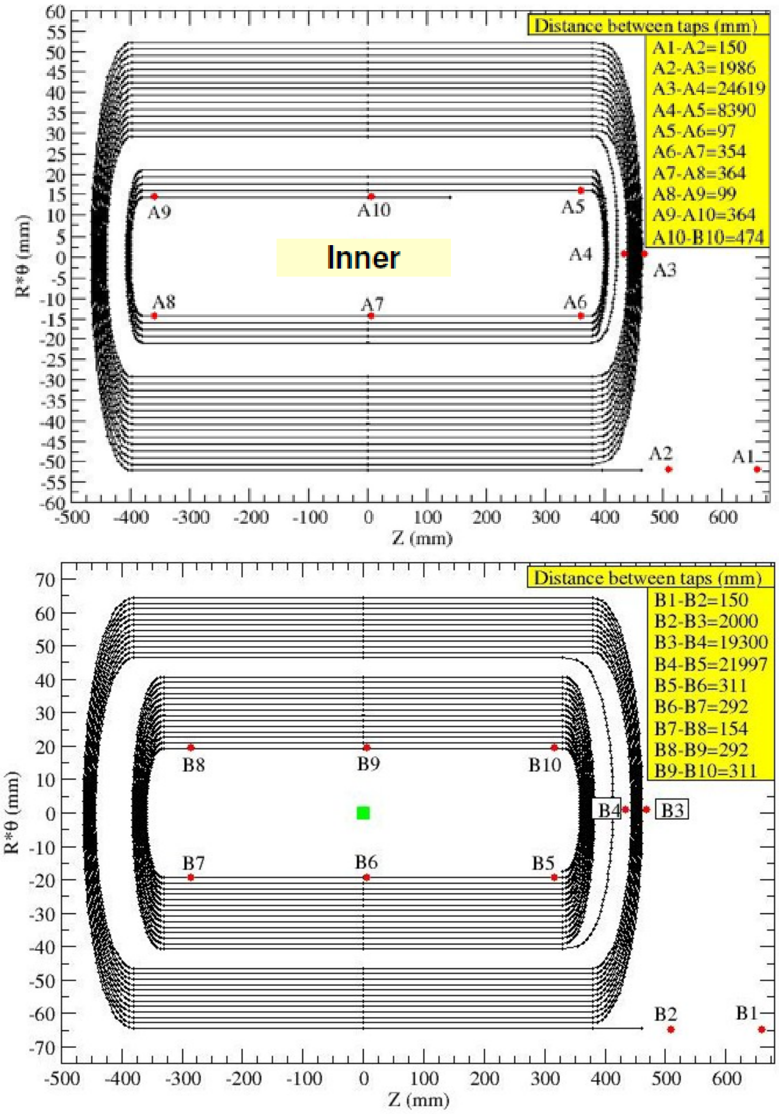

Fig. 3 HQM01 voltage tap locations for the inner (top) and outer (bottom) layers

3. Quench History

The magnet test program started with quench training at a ramp rate of 20 A/s and a temperature of 4.6 K. Due to a series of trips induced by voltage spikes (flux jumps) the quench detection thresholds and ramping profile were adjusted. For ~~the~~ quench training we were ramping at 200 A/s up to 4-5 kA, then at 50 A/s up to 9-10 kA and at 20 A/s until a quench occurred. This ramping profile is based on our past experience of testing magnets with large voltage spikes - voltage spikes are smaller at high ramp rates and are predominately at low current (low field instability).

HQM01 quench history is presented in Figs. 4 and 5. The first two quenches at 20 A/s initiated in the mid-plane turn (**A2_A3** in Fig. 3) of the inner coil layer. The next quench developed in the pole turn of the inner coil layer, but then two quenches initiated again in the mid-plane segment, at approximately the same current 12.9-13.1 kA without signs of training.

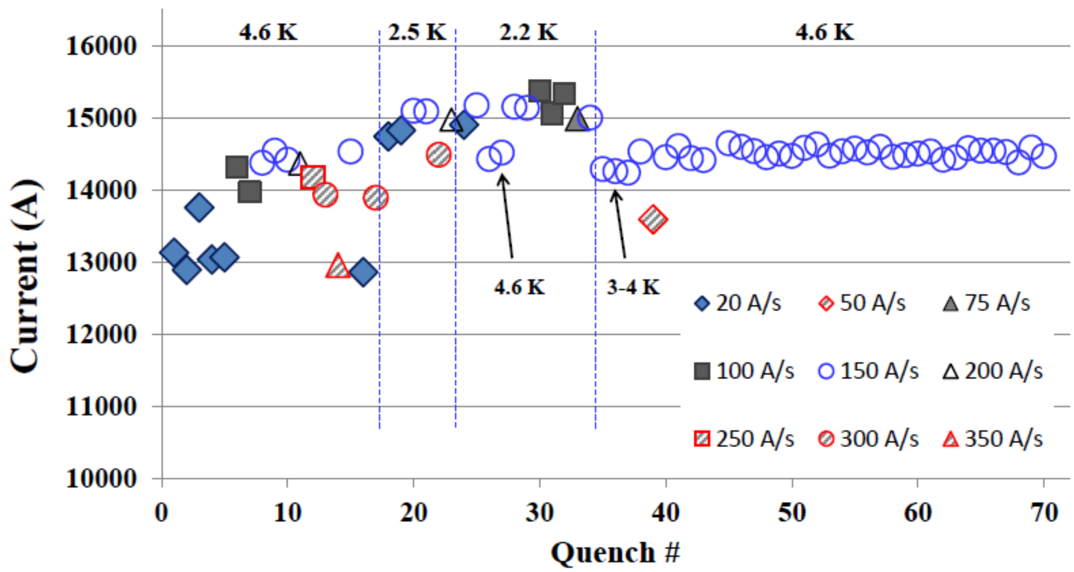

Fig. 4 HQM01 quench history with bath temperature and current ramp rate.

When the ramp rate was increased to 100 A/s the quench current reached 14-14.3 kA, but again one quench developed in the pole turn and the other one in the mid-plane segment. Further increase of ramp rate showed that the quench current reached the maximum at a ramp rate of 150 A/s then gradually decreased at higher ramp rates. Quenches at ramp rates up to 300 A/s still were initiated in **A2_A3** segment and only at 350 A/s quench developed both in the inner and outer layer multi-turn mid-plane segments **A3_A4** and **B4_B3**. After ramp rate study at 4.6 K quench current reproducibility was demonstrated at the 150 A/s, 20 A/s and 300 A/s ramp rates - the magnet quenched in the same location (mid-plane segment) and at the same currents (see Fig. 4). Apparently the mid-plane segment of the inner coil layer was limiting the quench performance and the magnet reached only 82% of short sample limit (SSL) at 4.6 K.

The test continued at 2.5 K and then at 2.2 K. The quench current increased at all ramp rates, but the inner-layer mid-plane segment continued to limit the magnet performance. No training was observed at lower temperatures as well and the magnet reached only 77% of SSL at 2.2 K. Estimates of the short sample limit for HQM01 at 4.6 K and 2.2 K are shown in Attachment I.

Based on our experience, quenches in a low field area could be related to lower conductor stability. So-called holding current tests were performed both at 4.6 K and 2.2 K. At 4.6 K spontaneous quenches were observed with holding currents between 14.4 kA and 14 kA (from 81% to 79% of SSL), holding time varied from 2 to 20 s. Nothing specific was found in these quenches. The same location and similar quench onsets as in training quenches were observed (see Fig. 6). Only at 13.8 kA (78% of SSL) were we able to hold constant current for about 600 seconds.

At 2.2 K only one test was done at 14.6 kA (74% of SSL). The magnet was held at this current for about 500 seconds.

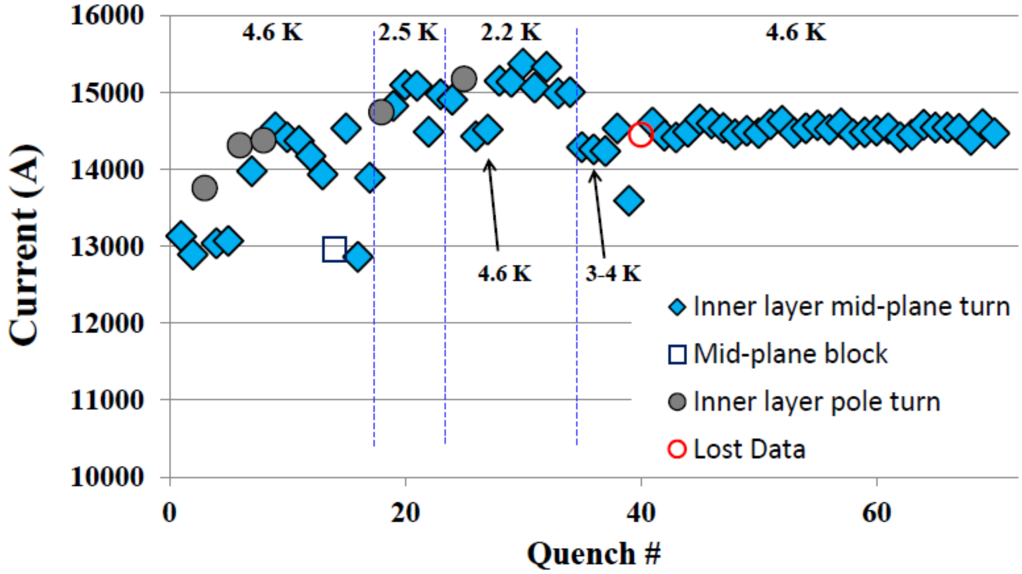

Fig. 5 Quench history of HQM01, showing location of each quench start

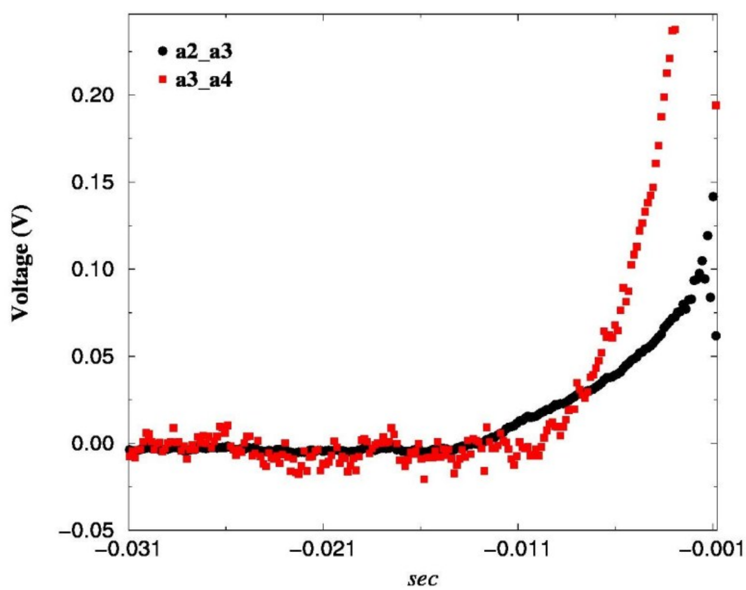

Fig. 6 Quench onset in the holding current test at 14.4 kA

At the end of the test several quenches were performed at 4.6 K for high MIITs studies. Results of this study, previously reported in [6], are presented in Section 8.

The residual resistivity ratio (RRR) was measured during magnet warm up. On average, RRR values varied from 260 to 320 (see Fig. 7).

A total of 70 quenches was recorded. In only 5 cases a quench developed in the inner layer pole block (see Fig. 5). The full quench history is presented in Tables 1 and 2.

We lost data for only one quench, number 40. No particular reasons were found for this failure and as a preventive measure we recommend to restart the data logger node every week.

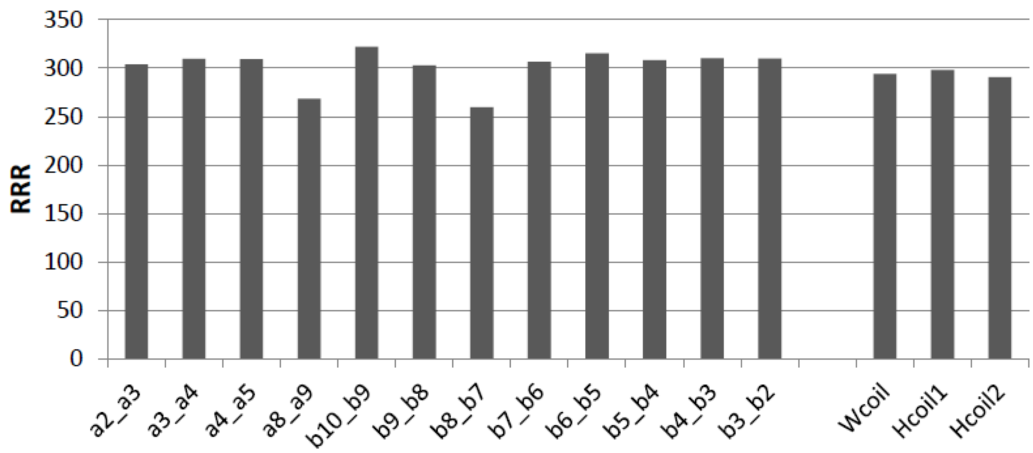

Fig. 7 RRR of HQM01 segments

3.1 Splice Resistance Measurements

Nb_3Sn-NbTi splice resistances were measured at both ends of the coil (**A1_A2** and **B2_B1** segments in Fig. 3) at 4.6 K. The magnet current varied from 2 kA to 14 kA. The splice voltages were digitized using HP 3458A digital multi-meter, integrating over 40 power line cycles and with 25-30 measurements recorded at each current setting.

Measurement data and linear fit to data are shown in Fig. 8. Splice resistances at both ends were found consistent 0.2-0.3 nOhm.

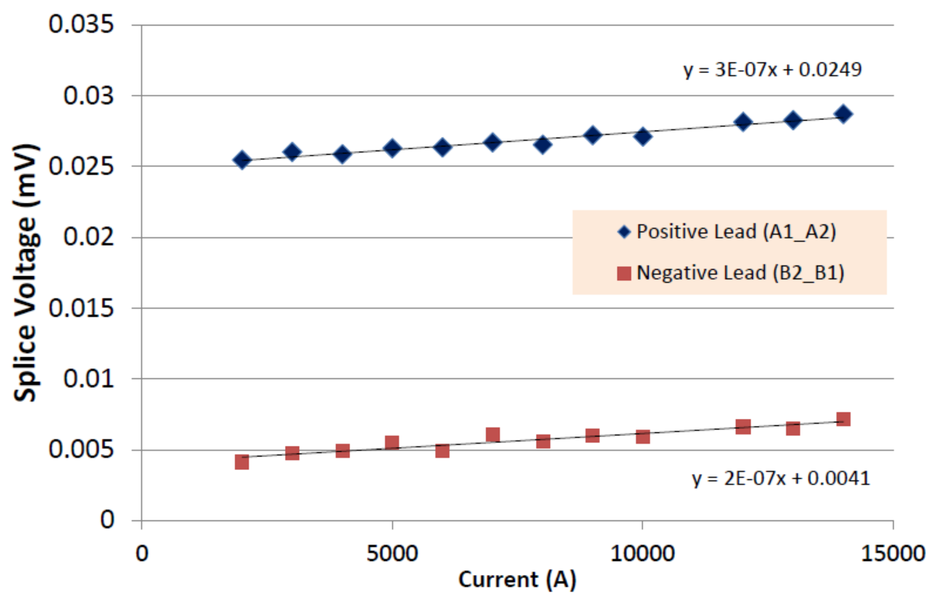

Fig. 8 Splice resistance measurements in HQM01

Table 1: HQM01 Quench History with comments

File	Quench #	Current (A)	dI/dt (A/sec)	t_{quench} (sec)	MIITs (10^6A^2s)	QDC	*Comments (online/offline)*
hqm01.Quench.110510123544.359		1000			0.05	GndRef	manual trip at 1000A after AQD balancing
hqm01.Quench.110510144653.733		93	20		0.02	SlWcoil	DQD lead trip at 100 A QLM verification
hqm01.Quench.110510155553.069		1500	20		1.77	WcoilIdot	manual trip, Gnd fault followed by AQD coils
hqm01.Quench.110510184501.405		4576	300		3.89	DQD leads	trip in DQD leads
hqm01.Quench.110511120110.971		5000			9.57	WcoilIdot	HFU2 testing at 200V, 9.6mF, HFU1 in protection 150V/9.6mF
hqm01.Quench.110511123351.786	**1**	13130	20	-0.0322	7.70	HcoilHcoil	quench at 13.1 kA, 20 A/s, (200A/s upto 4kA, 50A/s upto 8kA), 4.6K
hqm01.Quench.110511130856.934	**2**	12892	20	-0.0312	7.26	HcoilHcoil	quench at 12.9 kA, 20 A/s, 4.6 K
hqm01.Quench.110511144350.270	**3**	13754	20	-0.012	4.59	HcoilHcoil	quench at 13.8 kA, 20 A/s, 4.6K
hqm01.Quench.110511153802.063	**4**	13035	20	-0.3761	66.00	HcoilHcoil	quench at 13.1 kA, 20 A/s, 4.6K
hqm01.Quench.110511163503.163	**5**	13068	20	-0.0295	7.04	HcoilHcoil	quench at 13.1 kA, 20 A/s, 4.6Kto
hqm01.Quench.110511170031.760		14007	100	0.001	2.02	SlWcoil	trip in DQD leads
hqm01.Quench.110511172915.194	**6**	14311	100	-0.0091	4.32	HcoilHcoil	quench at 14.3 kA, 100 A/s (200 A/s to 4kA), 4.6K
hqm01.Quench.110511181038.405	**7**	13972	100	-0.3489	70.17	HcoilHcoil	quench at 14 kA, 100 A/s, 4.6K
hqm01.Quench.110511184152.279	**8**	14373	150	-0.0099	4.38	HcoilHcoil	quench at 14.4 kA, 150 A/s, 4.6K
hqm01.Quench.110512105450.757	**9**	14542	150	-0.0119	5.06	HcoilHcoil	quench at 14.6 kA, 150 A/s, 4.6 K
hqm01.Quench.110512112536.053	**10**	14416	150	-0.4978	105.42	HcoilHcoil	quench at 14.4 kA, 150 A/s (200 A/s upto 4kA), 4.6K
hqm01.Quench.110512120212.542	**11**	14366	200	-0.2251	48.83	HcoilHcoil	quench at 14.4 kA, 200 A/s, 4.6K
hqm01.Quench.110512141145.796	**12**	14168	250	-0.0169	5.85	HcoilHcoil	quench at 14.2 kA, 250 A/s, 4.6Ko
hqm01.Quench.110512144538.099	**13**	13930	300	-0.0162	5.36	HcoilHcoil	quench at 13.9 kA, 300 A/s, 4.6Ko
hqm01.Quench.110512151546.914	**14**	12960	350	-0.241	42.34	HcoilHcoil	quench at 12.9 kA, 350 A/s, 4.6K
hqm01.Quench.110512171037.615	**15**	14530	150	-0.192	42.81	HcoilHcoil	quench at 14.5 kA, 150 A/s, 4.6K
hqm01.Quench.110512173845.982	**16**	12860	20	-0.0504	10.42	HcoilHcoil	quench at 12.9 kA, 20 A/s (200,50,20) 4.6K
hqm01.Quench.110512181649.492	**17**	13890	300	-0.0175	5.71	HcoilHcoil	quench at 13.9 kA, 300 A/s, 4.6K
hqm01.Quench.110514114415.851		13582	20		1.93	SlWcoil	trip in AQD leads
hqm01.Quench.110514120747.913		14343	20		2.10	SlWcoil	trip in DQD leads
hqm01.Quench.110514125342.566	**18**	14740	20	-0.0109	4.80	HcoilHcoil	quench at 14.8kA, 20A/s, 2.5K
hqm01.Quench.110514132040.760	**19**	14822	20	-0.0123	5.31	HcoilHcoil	quench at 14.8kA, 20A/s, 2.5Krato
hqm01.Quench.110514140001.785	**20**	15094	150	-0.0711	18.88	HcoilHcoil	quench at 15.1 kA, 150 A/s, 2.5K
hqm01.Quench.110514143936.592	**21**	15079	150	-0.0413	12.07	HcoilHcoil	quench at 15.1 kA, 150 A/s, 2.5 K
hqm01.Quench.110514145454.144	**22**	14482	300	-0.0151	5.67	HcoilHcoil	quench at 14.5 kA, 300 A/s, 2.5K
hqm01.Quench.110514152547.072	**23**	14972	200	-0.0846	21.59	HcoilHcoil	quench at 15kA, 200 A/s, 2.5K

hqm01.Quench.110519113552.437	**24**	14906	20	-0.0155	6.10	WcoilIdot	quench at 14.9 kA, 20 A/s, 2.2Kto
hqm01.Quench.110519123537.901		14643	50		2.17	SlWcoil	holdiong 14.6 kA for 10min, then started ramping up at 50 A/s and the magnet quenches immediately 2.2K
hqm01.Quench.110519134153.204		14839	150		2.22	SlWcoil	DQD ClHolec tripped at 14.8 kA, 150 A/s, 2.2K
hqm01.Quench.110519150141.819		4871	150		13.63	HcoilHcoil	DQD leads tripped at 4kA, 150 A/s, 2.2 K
hqm01.Quench.110519160903.061		13714	150		1.95	SlWcoil	trip in AQD leads at 13.7 kA, 2.2 K
hqm01.Quench.110519164217.148		14568	150		2.14	SlWcoil	DQD Cleads tripped at 14.7 kA, 150 A/s, 2.2K
hqm01.Quench.110519172939.730	**25**	15172	150	-0.008	4.50	HcoilHcoil	quench at 15.2 kA, 150 A/s, 2.2K
hqm01.Quench.110520160334.578	**26**	14427	150	-0.213	46.64	HcoilHcoil	quench at 14.5 kA, 150 A/s, 4.5 K
hqm01.Quench.110523170736.444	**27**	14515	150	-0.014	5.54	HcoilHcoil	quench at 14.5 kA, 150 A/s, 4.6 K
hqm01.Quench.110524161157.415		5000			4.51	HcoilHcoil	PH test at 5 kA, HFU2 testing 250V, 4.8 mF, HFU1 protecting 120 V, 4.8 mF
hqm01.Quench.110524163639.619		5000			3.65	HcoilHcoil	HFU2 testing: 300 V/4.8 mF, HFU1 in prot. 120V/4.8 mF
hqm01.Quench.110524164914.023		5000			3.13	WcoilIdot	HFU2 testing: 350V/4.8 mF, HFU1 in prot. 120V/4.8mF
hqm01.Quench.110524170402.351		8000			2.91	HcoilHcoil	HFU2 testing 350 V/4.8 mF, HFU1 in prot. 120V/4.8mF
hqm01.Quench.110524173058.752		8000			3.06	WcoilIdot	HFU2 testing: 300V, 4.8mF, HFU1 in prot. 120V, 4.8mF
hqm01.Quench.110524175259.405		8000			3.20	WcoilIdot	HFU2 testing 250V, 4.8mF, HFU1 in prot. 120V, 4.8 mF
hqm01.Quench.110524181832.799		12000			5.01	HcoilHcoil	HFU2 testing: 250V, 4.8 mF, HFU1 in prot. 120V, 4.8mF
hqm01.Quench.110524183925.007		12000			4.71	HcoilHcoil	HFU2 testing 300V, 4.8mF, HFU1 in prot. 120V, 4.8mF
hqm01.Quench.110524190515.471		12000			4.46	HcoilHcoil	HFU2 testing 350V/4.8mF, HFU1 in protection 120V/4.8mF, 12 kA
hqm01.Quench.110525112647.946	**28**	15146	150	-0.0077	4.46	HcoilHcoil	quench at 15.1kA, 150 A/s, 2.2K
hqm01.Quench.110525120458.763	**29**	15133	150	-0.1201	30.18	HcoilHcoil	quench at 15.1 kA, 150A/s, 2.2K
hqm01.Quench.110525123114.459	**30**	15370	100	-0.009	4.89	HcoilHcoil	quench at 15.4 kA, 100 A/s, 2.2 K
hqm01.Quench.110525131226.131	**31**	15058	100	-0.0109	5.16	HcoilHcoil	quench at 15.1 kA, 100 A/s, 2.2K
hqm01.Quench.110525143450.134	**32**	15328	100	-0.0092	4.94	HcoilHcoil	quench at 15.3kA, 100A/s, 2.2K
hqm01.Quench.110525150116.973	**33**	14983	75	-0.0111	5.14	HcoilHcoil	quench at 15kA, 75 A/s, 2.2K
hqm01.Quench.110525152532.095	**34**	15003	150	-0.0186	6.86	WcoilIdot	quench at 15kA, 150 A/s, 2.2K
hqm01.Quench.110526092657.073	**35**	14287	150	-0.0914	21.13	HcoilHcoil	quench at 14.3kA, 150 A/s, 3K
hqm01.Quench.110526094843.573	**36**	14256	150	-0.0182	6.15	HcoilHcoil	quench at 14.2kA, 150 A/s, 3K
hqm01.Quench.110526110935.184	**37**	14234	150	-0.0182	6.15	HcoilHcoil	quench at 14.2 kA, 150A/s, 4K
hqm01.Quench.110526145312.543	**38**	14529	150	-0.0742	18.20	HcoilHcoil	quench at 14.5 kA, 150 A/s, 4.6K
hqm01.Quench.110526152736.678		14423			5.06	HcoilHcoil	Holding 14400A for 30sec. 4.6K

hqm01.Quench.110526163835.730		14316			5.81	HcoilHcoil	holding quench at 14300 A, 150 A/s, 4.6K
hqm01.Quench.110526165049.240	**39**	13588	50	-0.0277	7.41	HcoilHcoil	quench at 13.5 kA, trying to reach 14.3 kA at 50 A/s
hqm01.Quench.110526170117.056		14193	77		13.94	HcoilHcoil	quench at 14.2 kA, 150A/s, when ramping to 14.3kA,4.6K
hqm01.Quench.110526172118.747		14219	6		6.22	HcoilHcoil	quench at 14.2 kA, ramping to 14.2 kA, 150 A/s, 4.6K
hqm01.Quench.110526181957.125		13981	42		6.34	HcoilHcoil	ramp up&down, then to 14 kA. 150 A/s, 4.6K
hqm01.Quench.110526183704.917		13718	50		6.52	HcoilHcoil	holding quench, trying to reach 14kA.
hqm01.Quench.110527150638.441		14015			6.52	HcoilHcoil	holding 14 kA for 5 sec, 4.6K
hqm01.Quench.110527153955.016		14397	150		88.97	HcoilHcoil	quench at 14.4 kA, 150 A/s, after holding 13.8 kA for 10 min. 4.6K
hqm01.Quench.110527160759.157		5000			3.29	WcoilIdot	HFU2 (out NT) testing 250V, 9.6mF, HFU1 (all other PH in parallel) 120V, 9.6 mF
hqm01.Quench.110527163729.289		5000			2.93	WcoilIdot	HFU2: 300V, 9.6mF testing, HFU1: 120V, 9.6mF in protection, 5000A, 4.6K
hqm01.Quench.110527170159.767		8000			2.86	WcoilGnd	HFU2: 300V, 9.6mF testing, HFU1 120V, 9.6 mF protecting, 8 kA at 4.6K
hqm01.Quench.110527173649.812		8000			3.13	WcoilIdot	quench at 8000 A, HFU2 250V, 9.6 mF testing, HFU1: 120V, 9.6mF, 4.6K
hqm01.Quench.110527180658.158		12000			4.82	HcoilHcoil	HFU1 testing 250V, 9.6mF, HFU1 in protection 120V, 9.6mF, 12 kA at 4.6K
hqm01.Quench.110527182810.494		12000			4.62	HcoilHcoil	HFU2 testing: 300V, 9.6 mF, HFU1 in prot. 120V, 9.6 mF, 12 kA and 4,6K
hqm01.Quench.110531094732.505	**40**	14450	150				Lost Data
hqm01.Quench.110531103905.266		5000			0.49	WcoilIdot	manual trip at 5kA, no PH, dump delay 1 ms, T=4.6K
hqm01.Quench.110531111436.351		9000			1.27	WcoilGnd	manual trip at 9kA, no PH, dump delay 1ms, 4.6K
hqm01.Quench.110531113905.196		12000			1.58	SlWcoil	manual trip at 12kA, no PH, dump delay 1ms, 4.6K
hqm01.Quench.110531120651.897		12000			84.44	HcoilHcoil	manual trip at 12kA, now with PH, dump delay 1ms, 4.6K
hqm01.Quench.110531123334.818		9000			1.09	WcoilGnd	manual trip at 9kA, now with PH, dump delay 1ms, 4.6K
hqm01.Quench.110531140756.681	**41**	14604	150	-0.0157	6.17	HcoilHcoil	ramp to quench at 150A/s, dump delay 5ms, 4.6K
hqm01.Quench.110531143730.664	**42**	14437	150	-0.0176	8.97	HcoilHcoil	dump delay 15 ms, no delay in heaters, 4.6K
hqm01.Quench.110531150108.243	**43**	14412	150	-0.0184	6.22	HcoilHcoil	regular quench at 150A/s, 4.6K
hqm01.Quench.110531160146.969		9000			3.68	WcoilGnd	manual trip at 9kA, dump delay 1 ms, no PH, 4.6K
hqm01.Quench.110531162122.744		12000			5.39	SlWcoil	No PH, dump delay 1ms, manual trip at 12kA
hqm01.Quench.110531164748.210		12000			5.38	SlWcoil	Man. trip at 12kA, PH connected, dump delay 1ms,4.6 K
hqm01.Quench.110531171859.951	**44**	14486	150	-0.0146	10.84	HcoilHcoil	ramp to quench, dump delay 5 ms, 150 A/s, 4.6 K
hqm01.Quench.110531180342.355		12000			8.82	WcoilIdot	manual trip at 12 kA, dump delay 20 ms, 4.6 K

hqm01.Quench.110531182841.221		12000			7.85	SlWcoil	Man. trip, dump delay 20 ms, HFU at 350 V/9.6 mF, 4.6 K
hqm01.Quench.110531185439.576	**45**	14645	150	-0.0142	12.99	HcoilHcoil	quench at 14.6 kA, dump delay 20 ms, 150 A/s, 4.6 K
hqm01.Quench.110531192527.921	**46**	14594	150	-0.0144	13.96	HcoilHcoil	quench at 14.5 kA, 150 A/s, dump delay 30 ms, 4.6 K
hqm01.Quench.110601093558.220	**47**	14536	150	-0.016	10.30	HcoilHcoil	quench at regular settings, 150 A/s, 4.6K
hqm01.Quench.110601101458.076	**48**	14452	150	-0.0186	15.10	HcoilHcoil	dump delay 35 ms, 150 A/s, quench at 14.4 kA, 4.6 K
hqm01.Quench.110601111359.285	**49**	14500	150	-0.0165	10.49	HcoilHcoil	dump delay 1 ms, regular quench.
hqm01.Quench.110601115122.086	**50**	14468	150	-0.0153	13.93	HcoilHcoil	dump delay 35 ms, HFU at 350 V, 150 A/s, 4.6 K
hqm01.Quench.110601121718.081	**51**	14581	150	-0.0184	15.47	HcoilHcoil	dump delay 40 ms, 150 A/s, HFU 200V again, 4.6K
hqm01.Quench.110601130024.082	**52**	14629	150	-0.0152	15.20	HcoilHcoil	dump delay 45 ms, 150 A/s, 4.6 K
hqm01.Quench.110601151329.388	**53**	14473	150	-0.0168	16.00	HcoilHcoil	dump delay 55 ms, 150 A/s, 4.6 K
hqm01.Quench.110601153403.996	**54**	14533	150	-0.0161	10.48	HcoilHcoil	regular quench, 150 A/s, dump delay 1 ms, 4.6 K
hqm01.Quench.110601160519.951	**55**	14571	150	-0.0147	16.18	HcoilHcoil	dump delay 70 ms, 150 A/s, 4.6 K
hqm01.Quench.110601164204.260	**56**	14518	150	-0.0158	15.67	HcoilHcoil	dump delay 70 ms, HFU voltage is 350 V, 150 A/s, 4.6 K
hqm01.Quench.110601173333.464	**57**	14594	150	-0.0149	16.72	HcoilHcoil	dump delay 90 ms, HFU voltage 200 V, 150 A/s, 4.6 K
hqm01.Quench.110601175620.181	**58**	14455	150	-0.0155	17.10	HcoilHcoil	dump delay 120 ms, 150 A/s, 4.6 K
hqm01.Quench.110601183032.039	**59**	14478	150	-0.0144	10.07	HcoilHcoil	regular quenchm 150 A/s, dump delay 1 ms, 4.6 K
hqm01.Quench.110602113335.809	**60**	14500	150	-0.0158	16.43	HcoilHcoil	dump delay 1000ms, HFU voltage 350 V, 150 A/s, 4.6 K
hqm01.Quench.110602123313.772		14268	150	-0.0071	14.46	HcoilHcoil	HFU2 testing (outer layer PH), HFU1 (inner PH) in protection, both at 350 V, 150 V, HFU2 fires at 14.2 kA
hqm01.Quench.110602131638.635		14289	150	-0.0064	14.81	HcoilHcoil	HFU2 testing (outer PH), HFU1 in protection (inner PH), HFU delay 30 ms, 150 A/s, HFU2 fired at 14.3 kA
hqm01.Quench.110602143514.099	**61**	14531	150	-0.0154	18.75	HcoilHcoil	dump delay 1000ms, PH delay 15 ms, 150 A/s, 4.6 K
hqm01.Quench.110602152531.599	**62**	14415	150	-0.0181	20.11	HcoilHcoil	dump delay 1000ms, PH delay 25 ms, 150 A/s, 4.6 K
hqm01.Quench.110602155426.823	**63**	14447	150	-0.0184	20.78	HcoilHcoil	dump delay 1000ms, PH delay 40 ms, 150 A/s
hqm01.Quench.110602163411.632	**64**	14576	150	-0.0182	18.11	HcoilHcoil	dump delay 1000ms, PH delay 0ms, inner PH removed
hqm01.Quench.110602165746.888	**65**	14540	150	-0.018	20.38	HcoilHcoil	dump delay 1000 ms, PH delay 25 ms, inner PH removed
hqm01.Quench.110603093223.598	**66**	14540	150	-0.0182	20.73	HcoilHcoil	dump delay 1000ms, only OL PH at 40 ms, inner PH removed, 150A/s
hqm01.Quench.110603130053.249	**67**	14523	150	-0.0163	20.78	HcoilHcoil	dump delay 1000 ms, no heaters, 150 A/s, 4.6 K
hqm01.Quench.110603143759.599	**68**	14380	150	-0.0184	20.70	HcoilHcoil	dump delay 1000 ms, PH delay 150 ms, 150 A/s, 4.6K
hqm01.Quench.110603151818.717	**69**	14587	150	-0.017	10.69	HcoilHcoil	regular quench, 150 A/s, 4.6 K
hqm01.Quench.110603165418.615	**70**	14467	150	-0.0186	10.89	HcoilHcoil	w/o active gnd fault system - to check noise level. 150 A/s

Table 2: HQM01 Quench History with parameters for the first two quenching segments

File	Quench #	Current (A)	dI/dt (A/sec)	1st Vtap seg	trise (sec)	2nd Vtap seg	trise (sec)	Mag. Bot. Temp (K)	Mag Top Temp (K)
hqm01.Quench.110510123544.359		1000		a10_b10	0.0007	a1_a2	0.0007	4.593	4.590
hqm01.Quench.110510144653.733		93	20	a10_b10	-0.0001	a1_a2	-0.0001	4.594	4.589
hqm01.Quench.110510155553.069		1502	20	a2_a3	0.0155	b3_b2	0.0157	4.593	4.587
hqm01.Quench.110510184501.405		4576	300					4.599	4.599
hqm01.Quench.110511120110.971		5000		a7_a8	-0.1070	a8_a9	-0.0294	4.599	4.592
hqm01.Quench.110511123351.786	**1**	13130	20	a2_a3	-0.0284	a3_a4	-0.0269	4.602	4.599
hqm01.Quench.110511130856.934	**2**	12892	20	a2_a3	-0.0297	a3_a4	-0.0239	4.605	4.603
hqm01.Quench.110511144350.270	**3**	13754	20	a9_b10	-0.0142	a4_a5	-0.0120	4.591	4.588
hqm01.Quench.110511153802.063	**4**	13035	20	a2_a3	-0.0245	a3_a4	0.0010	4.593	4.591
hqm01.Quench.110511163503.163	**5**	13068	20	a2_a3	-0.0262	a3_a4	-0.0259	4.586	4.580
hqm01.Quench.110511170031.760		14007	100					4.588	4.590
hqm01.Quench.110511172915.194	**6**	14311	100	a9_a10	-0.0116	a5_a7	-0.0085	4.588	4.590
hqm01.Quench.110511181038.405	**7**	13972	100	a2_a3	-0.0182			4.583	4.579
hqm01.Quench.110511184152.279	**8**	14373	150	a5_a7	-0.0095			4.589	4.589
hqm01.Quench.110512105450.757	**9**	14542	150	a2_a3	-0.0120	a3_a4	-0.0109	4.607	4.603
hqm01.Quench.110512112536.053	**10**	14416	150	a2_a3	-0.0146	a3_a4	-0.0096	4.597	4.591
hqm01.Quench.110512120212.542	**11**	14366	200	a2_a3	-0.0143	a3_a4	0.0010	4.591	4.589
hqm01.Quench.110512141145.796	**12**	14168	250	a2_a3	-0.0143	a3_a4	-0.0143	4.588	4.586
hqm01.Quench.110512144538.099	**13**	13930	300	a2_a3	-0.0151	a3_a4	-0.0151	4.592	4.588
hqm01.Quench.110512151546.914	**14**	12960	350	a3_a4	-0.0106	a2_a3	-0.0074	4.593	4.592
hqm01.Quench.110512171037.615	**15**	14530	150	a2_a3	0.0001	a3_a4	0.0003	4.589	4.584
hqm01.Quench.110512173845.982	**16**	12860	20	a2_a3	-0.0297	a3_a4	-0.0294	4.593	4.592
hqm01.Quench.110512181649.492	**17**	13890	300	a2_a3	-0.0151	a3_a4	-0.0134	4.574	4.570
hqm01.Quench.110514114415.851		13582	20					2.451	2.498
hqm01.Quench.110514120747.913		14343	20					2.376	2.434
hqm01.Quench.110514125342.566	**18**	14740	20	a9_a10	-0.0095	a4_a5	-0.0091	2.489	2.521
hqm01.Quench.110514132040.760	**19**	14822	20	a2_a3	-0.0099	a3_a4	-0.0052	2.447	2.507
hqm01.Quench.110514140001.785	**20**	15094	150	a2_a3	-0.0115	b3_b2	-0.0072	2.407	2.512
hqm01.Quench.110514143936.592	**21**	15079	150	a2_a3	-0.0059	a3_a4	-0.0056	2.419	2.483
hqm01.Quench.110514145454.144	**22**	14482	300	a2_a3	-0.0136	a3_a4	-0.0118	2.472	2.472
hqm01.Quench.110514152547.072	**23**	14972	200	a2_a3	-0.0090	a3_a4	-0.0045	2.376	2.483
hqm01.Quench.110519113552.437	**24**	14906	20	a2_a3	-0.0126	a3_a4	-0.0122	2.168	2.167

hqm01.Quench.110519123537.901		14643	50	a1_a2	0.0006	b10_b9	0.0007	2.154	2.151
hqm01.Quench.110519134153.204		14839	150					2.148	2.144
hqm01.Quench.110519150141.819		4871	150					2.153	2.152
hqm01.Quench.110519160903.061		13714	150					2.155	2.153
hqm01.Quench.110519164217.148		14568	150					2.157	2.153
hqm01.Quench.110519172939.730	**25**	15172	150	a9_b10	-0.0104	a4_a5	-0.0083	2.154	2.152
hqm01.Quench.110520160334.578	**26**	14427	150	a2_a3	-0.0156	a3_a4	-0.0084	4.568	4.565
hqm01.Quench.110523170736.444	**27**	14515	150	a2_a3	-0.0120	a3_a4	-0.0118	4.585	4.583
hqm01.Quench.110524161157.415		5000		b6_b5	-0.1229			4.591	4.589
hqm01.Quench.110524163639.619		5000		b5_b4	-0.0927			4.589	4.588
hqm01.Quench.110524164914.023		5000		b5_b4	-0.0871			4.597	4.598
hqm01.Quench.110524170402.351		8000		b5_b4	-0.0178			4.590	4.588
hqm01.Quench.110524173058.752		8000		b5_b4	-0.0200			4.614	4.613
hqm01.Quench.110524175259.405		8000		b5_b4	-0.0230			4.626	4.623
hqm01.Quench.110524181832.799		12000		b5_b4	-0.0132			4.623	4.624
hqm01.Quench.110524183925.007		12000		b5_b4	-0.0133			4.625	4.623
hqm01.Quench.110524190515.471		12000		b5_b4	-0.0116			4.630	4.633
hqm01.Quench.110525112647.946	**28**	15146	150	a2_a3	-0.0081	a3_a4	-0.0067	2.163	2.158
hqm01.Quench.110525120458.763	**29**	15133	150	a2_a3	-0.0080	a3_a4	-0.0080	2.167	2.165
hqm01.Quench.110525123114.459	**30**	15370	100	a2_a3	-0.0087	a3_a4	-0.0078	2.148	2.147
hqm01.Quench.110525131226.131	**31**	15058	100	a2_a3	-0.0081	a3_a4	-0.0073	2.153	2.151
hqm01.Quench.110525143450.134	**32**	15328	100	a2_a3	-0.0084	a3_a4	-0.0059	2.153	2.153
hqm01.Quench.110525150116.973	**33**	14983	75	a2_a3	-0.0091	a3_a4	-0.0085	2.154	2.152
hqm01.Quench.110525152532.095	**34**	15003	150	a2_a3	-0.0120	a3_a4	-0.0063	2.156	2.155
hqm01.Quench.110526092657.073	**35**	14287	150	a2_a3	-0.0120	a3_a4	-0.0052	2.880	2.971
hqm01.Quench.110526094843.573	**36**	14256	150	a2_a3	-0.0164	a3_a4	-0.0150	2.993	3.006
hqm01.Quench.110526110935.184	**37**	14234	150	a2_a3	-0.0127	a3_a4	-0.0109	4.018	4.032
hqm01.Quench.110526145312.543	**38**	14529	150	a2_a3	-0.0109	a3_a4	-0.0101	4.587	4.585
hqm01.Quench.110526152736.678		14423		a2_a3	-0.0130	a3_a4	-0.0088	4.591	4.587
hqm01.Quench.110526163835.730		14316		a2_a3	-0.0140	a1_a2	-0.0118	4.582	4.582
hqm01.Quench.110526165049.240	**39**	13588	50	a2_a3	-0.0224	a1_a2	-0.0216	4.601	4.603
hqm01.Quench.110526170117.056		14193	77	a2_a3	-0.0181	a1_a2	-0.0178	4.596	4.598
hqm01.Quench.110526172118.747		14219	6	a2_a3	-0.0179	a1_a2	-0.0165	4.600	4.601
hqm01.Quench.110526181957.125		13981	42	a2_a3	-0.0164	a1_a2	-0.0161	4.568	4.565

hqm01.Quench.110526183704.917		13718	50	a2_a3	-0.0202	a1_a2	-0.0200	4.566	4.564
hqm01.Quench.110527150638.441		14015		a2_a3	-0.0202	a1_a2	-0.0174	4.588	4.585
hqm01.Quench.110527153955.016		14397	150	a2_a3	-0.0143	a3_a4	-0.0085	4.618	4.615
hqm01.Quench.110527160759.157		5000		b5_b4	-0.0902			4.610	4.605
hqm01.Quench.110527163729.289		5000		b5_b4	-0.0839			4.594	4.591
hqm01.Quench.110527170159.767		8000		b5_b4	-0.0186			4.601	4.598
hqm01.Quench.110527173649.812		8000		b5_b4	-0.0228			4.583	4.579
hqm01.Quench.110527180658.158		12000		b5_b4	-0.0134			4.587	4.584
hqm01.Quench.110527182810.494		12000		b5_b4	-0.0130			4.583	4.577
hqm01.Quench.110531094732.505	**40**	14450	150	Lost Data		Lost Data			
hqm01.Quench.110531103905.266		5000						4.581	4.579
hqm01.Quench.110531111436.351		9000						4.581	4.577
hqm01.Quench.110531113905.196		12000						4.581	4.576
hqm01.Quench.110531120651.897		12000						4.593	4.591
hqm01.Quench.110531123334.818		9000						4.586	4.585
hqm01.Quench.110531140756.681	**41**	14604	150	a2_a3	-0.0157	a3_a4	-0.0108	4.571	4.569
hqm01.Quench.110531143730.664	**42**	14437	150	a2_a3	-0.0176	a3_a4	-0.0046	4.589	4.590
hqm01.Quench.110531150108.243	**43**	14412	150	a2_a3	-0.0184	a3_a4	0.0010	4.595	4.593
hqm01.Quench.110531160146.969		9000						4.570	4.568
hqm01.Quench.110531162122.744		12000						4.578	4.576
hqm01.Quench.110531164748.210		12000						4.583	4.583
hqm01.Quench.110531171859.951	**44**	14486	150	a2_a3	-0.0146	a3_a4	-0.0046	4.583	4.582
hqm01.Quench.110531180342.355		12000						4.582	4.579
hqm01.Quench.110531182841.221		12000						4.577	4.575
hqm01.Quench.110531185439.576	**45**	14645	150	a2_a3	-0.0142	a3_a4	-0.0084	4.588	4.587
hqm01.Quench.110531192527.921	**46**	14594	150	a2_a3	-0.0144	a3_a4	-0.0074	4.585	4.579
hqm01.Quench.110601093558.220	**47**	14536	150	a2_a3	-0.0160	a3_a4	-0.0081	4.588	4.589
hqm01.Quench.110601101458.076	**48**	14452	150	a2_a3	-0.0186	a3_a4	-0.0085	4.588	4.592
hqm01.Quench.110601111359.285	**49**	14500	150	a2_a3	-0.0165	a3_a4	-0.0082	4.587	4.587
hqm01.Quench.110601115122.086	**50**	14468	150	a2_a3	-0.0153	a3_a4	-0.0084	4.583	4.581
hqm01.Quench.110601121718.081	**51**	14581	150	a2_a3	-0.0184	a3_a4	-0.0079	4.606	4.605
hqm01.Quench.110601130024.082	**52**	14629	150	a2_a3	-0.0152	a3_a4	-0.0079	4.589	4.587
hqm01.Quench.110601151329.388	**53**	14473	150	a2_a3	-0.0168	a3_a4	-0.0074	4.529	4.530

hqm01.Quench.110601153403.996	**54**	14533	150	a2_a3	-0.0161	a3_a4	-0.0078	4.572	4.563
hqm01.Quench.110601160519.951	**55**	14571	150	a2_a3	-0.0147	a3_a4	-0.0074	4.548	4.547
hqm01.Quench.110601164204.260	**56**	14518	150	a2_a3	-0.0158	a3_a4	-0.0082	4.552	4.552
hqm01.Quench.110601173333.464	**57**	14594	150	a2_a3	-0.0149	a3_a4	-0.0083	4.544	4.545
hqm01.Quench.110601175620.181	**58**	14455	150	a2_a3	-0.0155	a3_a4	-0.0081	4.619	4.621
hqm01.Quench.110601183032.039	**59**	14478	150	a2_a3	-0.0144	a3_a4	-0.0076	4.607	4.613
hqm01.Quench.110602113335.809	**60**	14500	150	a2_a3	-0.0158	a3_a4	-0.0084	4.591	4.586
hqm01.Quench.110602123313.772		14268	150	b8_b7	-0.0071	b5_b4	-0.0053	4.603	4.602
hqm01.Quench.110602131638.635		14289	150	b8_b7	-0.0064	b5_b4	-0.0049	4.608	4.601
hqm01.Quench.110602143514.099	**61**	14531	150	a2_a3	-0.0154	a3_a4	-0.0074	4.577	4.575
hqm01.Quench.110602152531.599	**62**	14415	150	a2_a3	-0.0181	a3_a4	-0.0084	4.585	4.585
hqm01.Quench.110602155426.823	**63**	14447	150	a2_a3	-0.0184	a3_a4	-0.0086	4.563	4.566
hqm01.Quench.110602163411.632	**64**	14576	150	a2_a3	-0.0182	a3_a4	-0.0078	4.569	4.568
hqm01.Quench.110602165746.888	**65**	14540	150	a2_a3	-0.0180	a3_a4	-0.0081	4.565	4.566
hqm01.Quench.110603093223.598	**66**	14540	150	a2_a3	-0.0182	a3_a4	-0.0083	4.592	4.594
hqm01.Quench.110603130053.249	**67**	14523	150	a2_a3	-0.0163	a3_a4	-0.0076	4.579	4.577
hqm01.Quench.110603143759.599	**68**	14380	150	a2_a3	-0.0184	a3_a4	-0.0087	4.570	4.568
hqm01.Quench.110603151818.717	**69**	14587	150	a2_a3	-0.0170	a3_a4	-0.0078	4.577	4.574
hqm01.Quench.110603165418.615	**70**	14467	150	a2_a3	-0.0186	a3_a4	-0.0079	4.572	4.574

4. Ramp Rate and Temperature Dependence

Ramp rate dependence of the quench current at different temperatures is presented in Fig. 9. Since HQM01 did not exhibit training, average quench currents are shown for multiple quenches at the same ramp rate. Ramp rate dependence of the HQ01d quadrupole with a similar conductor but without stainless steel core in the cable, is also shown for comparison. The HQ01d magnet was tested at LBNL and test results are presented in [7]. Although the magnetic flux distribution in the mid-plane block is different for mirror and quadrupole magnets, the effect of using a SS core in the cable can be clearly seen in Fig. 9.

All HQM01 ramp rate quenches, except for one at 350 A/s, developed in the mid-plane segment **A2_A3**. At a temperature of 4.6 K and **a** ramp rate of 350 A/s**,** a single quench developed in mid-plane multi-turn segments both of the inner and outer coil layers (**A3_A4** and **B4_b3**).

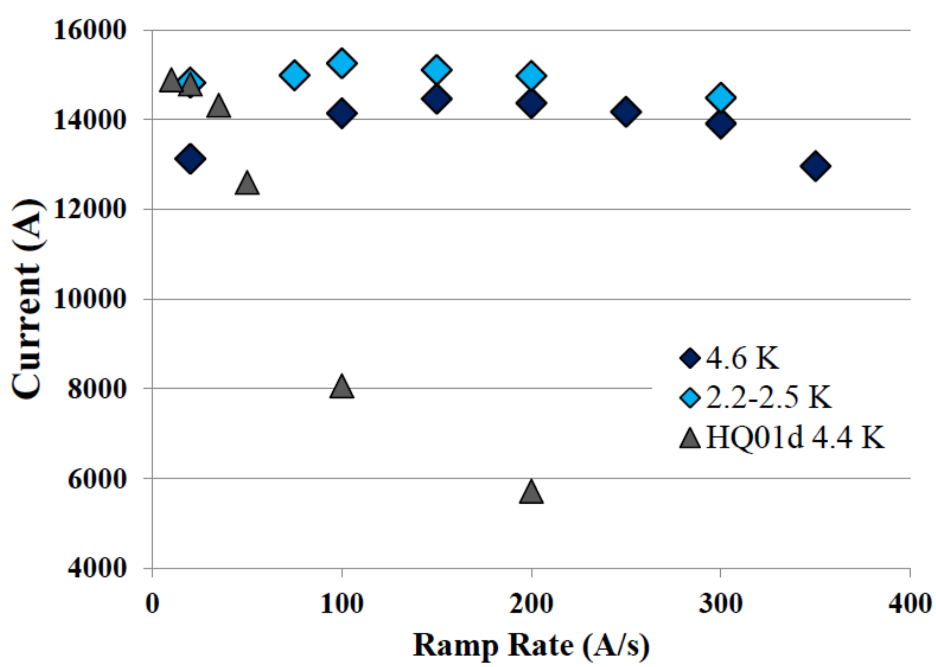

Fig. 9 HQM01 ramp rate dependence at 4.6 K and 2.2 K. Also shown for comparison is the HQ01d ramp rate dependence at 4.4 K.

Temperature dependence of the quench current is presented in Fig. 10. For consistency, only quenches at 150 A/s are shown in this figure. Ramps at intermediate temperatures (3 K and 4 K) were done during the warm-up from 2.2 K to 4.6 K. At 2.2-2.5 K quench currents are on average higher and at intermediate temperatures slightly lower than at 4.6 K.

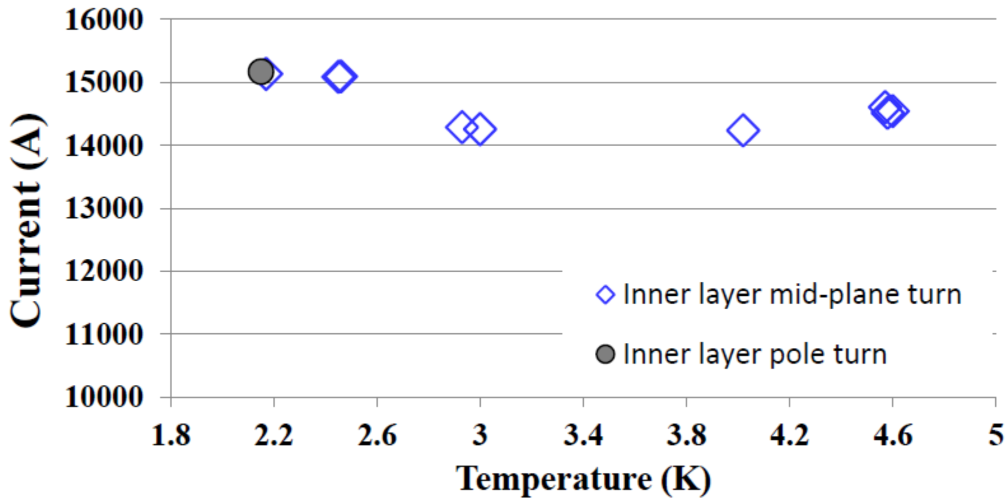

Fig. 10 HQM01 temperature dependence

5. Quench Locations

Voltage tap segments and their lengths are listed in Fig. 3. Most training or ramp rate quenches developed in the same mid-plane single turn segment of the inner coil layer **(A2_A3)**. Only 5 quenches developed in the inner layer pole-turn segments and one ramp rate quench developed in the mid-plane multi-turn segments of the inner and outer coil layers.

For further localization of quenches we used the pc-board (PCB) based quench antenna mounted on the flat surface of the iron mirror block (see Fig. 1, left). PCB quench antenna locations with respect to voltage taps on the inner coil layer are shown in Fig. 11.

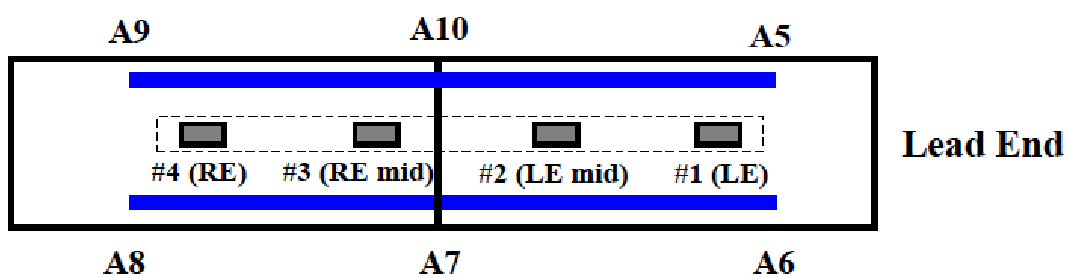

Fig. 11 PCB quench antenna location in HQM01.

All quenches in the mid-plane single-turn segment were first detected in quench antenna #3 or #4. Quenches in the pole-turn block and one ramp-rate quench with the quench antenna information are shown in Table 3.

Table 3. Quenches in the pole-turn block with the quench antenna information

Quench #	I (A)	Temp (K)	ramp rate, A/s	1st seg.	1st time	QA #	T (QA) ms
3	13754	4.59	20	a9_b10	-14.2	1 (LE)	-13.1
6	14310	4.59	100	a9_b10	-11.6	2 (LE mid)	-11.4
8	14375	4.59	150	a5_7	-11.2	4 (RE)	-10
14	12960	4.59	350	a3_4	-10.4	4 (RE)	-10.7
18	14740	2.51	20	a9_b10	-11.8	4 (RE)	-12.1
25	15172	2.15	150	a9_b10	-10.4	2 (LE mid)	-10.2

6. Strain Gauge Data

The HQM01 mechanical behavior during cool-down, test, and warm-up were monitored with strain gauges mounted on support structure components and coil. The coil was instrumented with full bridge azimuthal and axial gauges located in the middle of Titanium pole piece of the inner coil layer. A total of eight bullet-type gauges are used to measure the end forces, two per "bullet" and 2 'bullets" per end. Readings of 2 gauges on the same bullet were averaged to eliminate strains due to bending.

The skin was instrumented with the standard set of strain gauges at 90 and 60 degrees in an azimuthal plane both on the upper and lower half-skins (see Fig. 12).

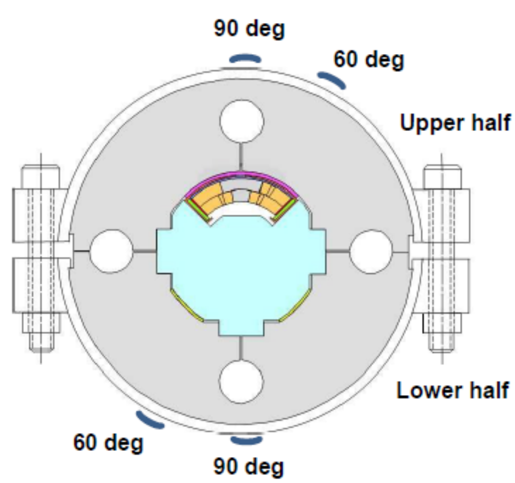

Fig. 12 Skin strain gauges

One compensating gauge was placed at each end of the magnet and one on the upper half-skin.

In total, 21 strain gauges were used in HQM01. Only strains are shown below in all plots.

6.1 Cool-down

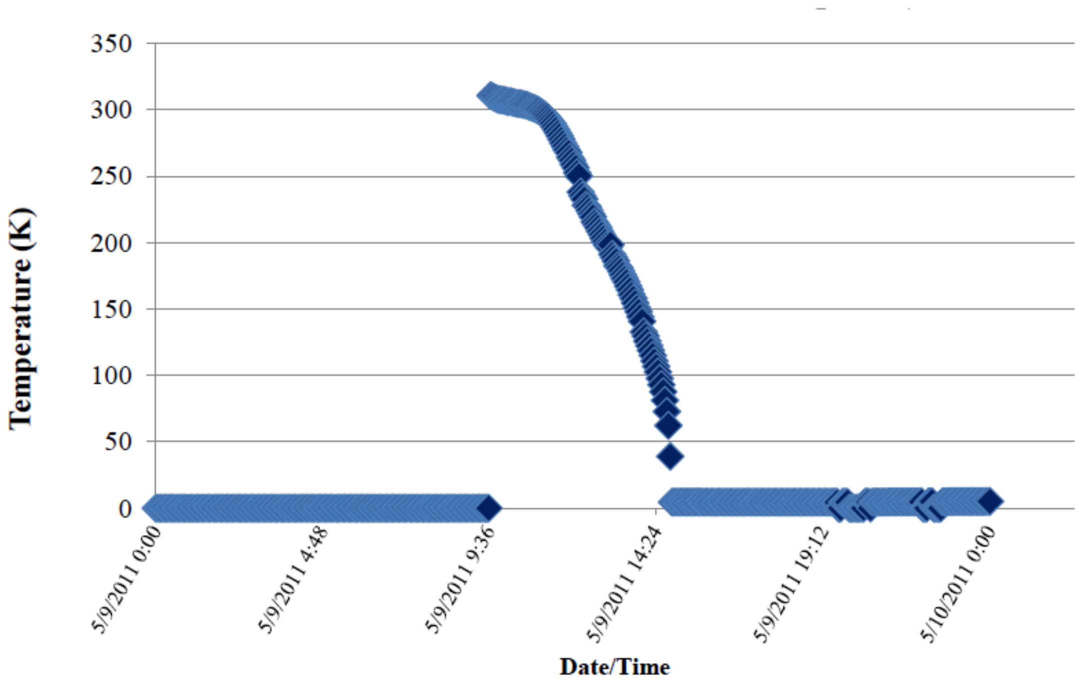

Fig. 13 Temperature of the magnet skin (top) measured during cool-down vs. time

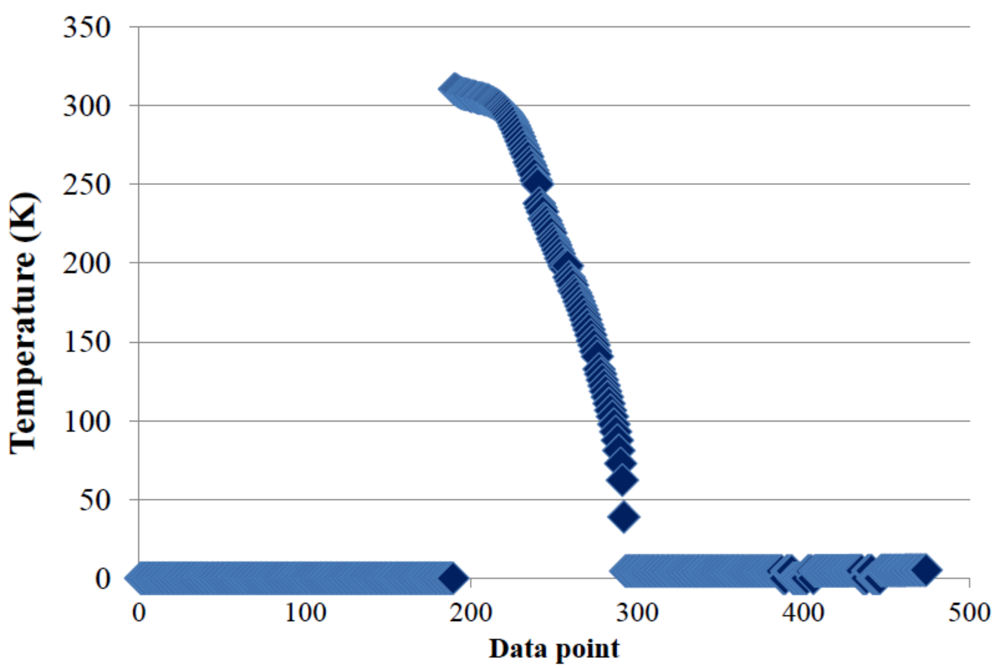

Fig. 14 Temperature of the magnet skin (top) measured during cool-down vs. data point

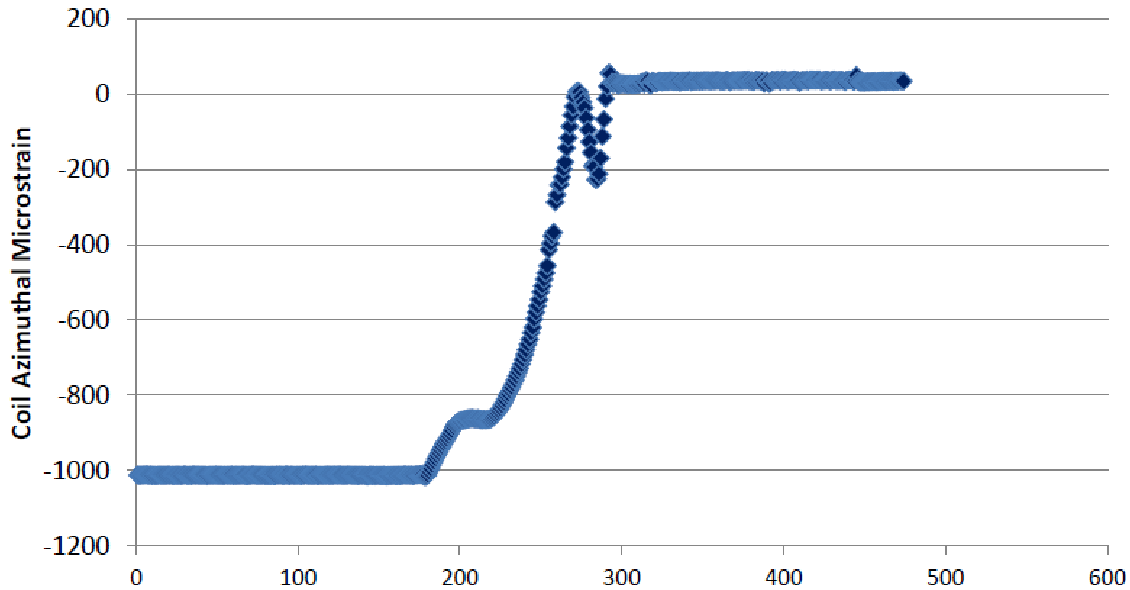

Fig 15 Azimuthal microstrain in the coil pole measured during cool-down

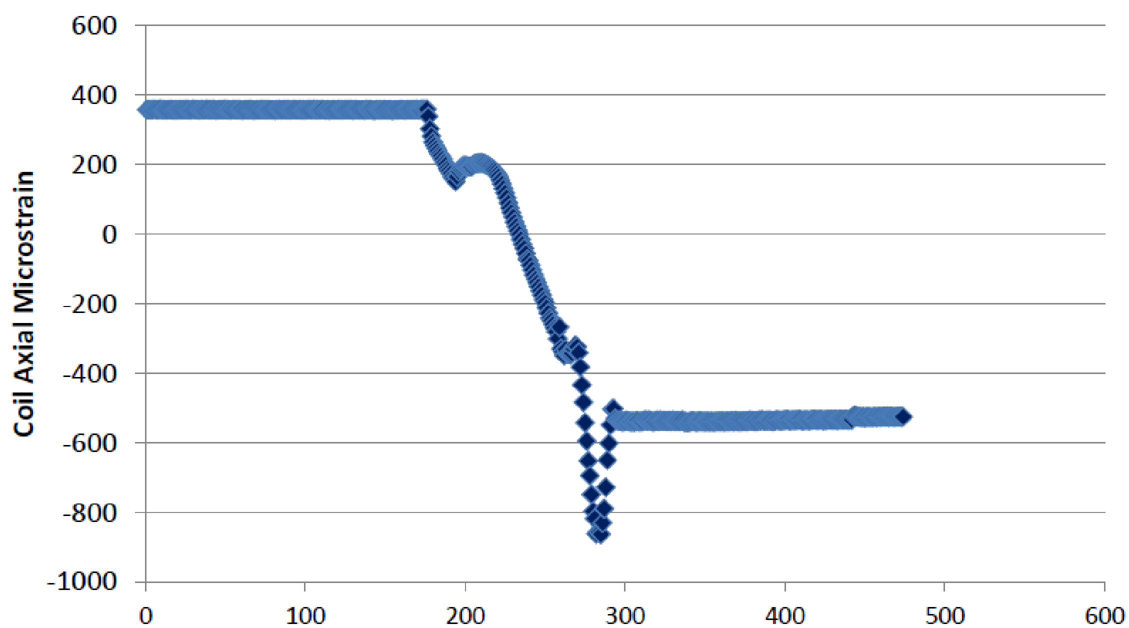

Fig 16 Axial microstrain in the coil pole measured during cool-down

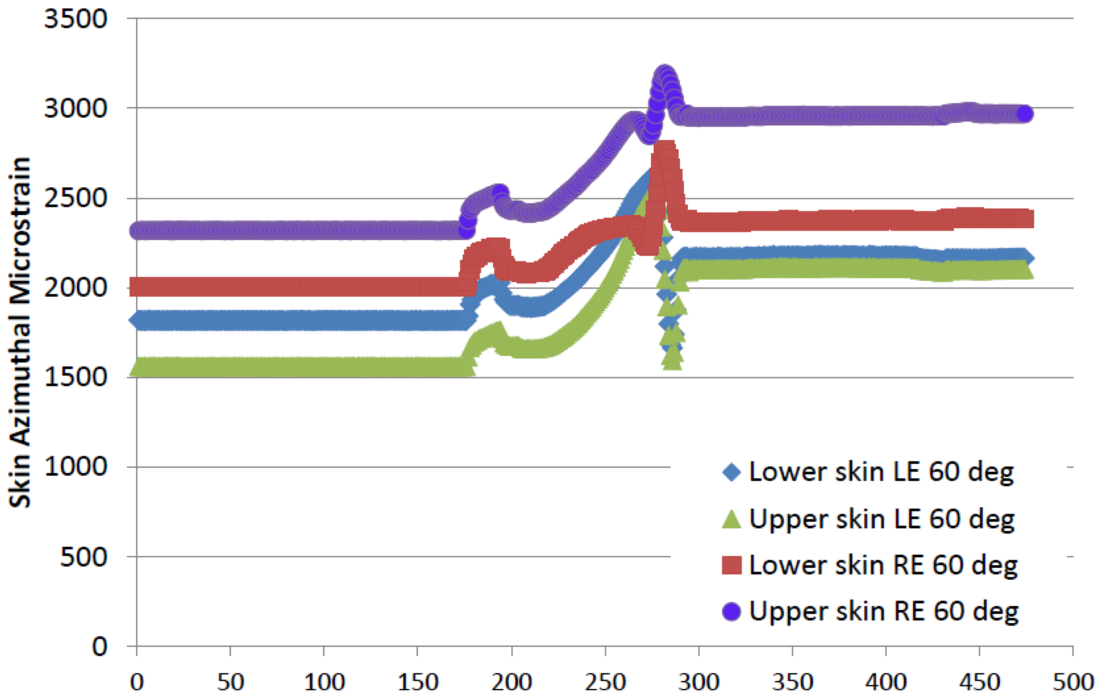

Fig 17 Skin gauges at 60 deg. during cool-down

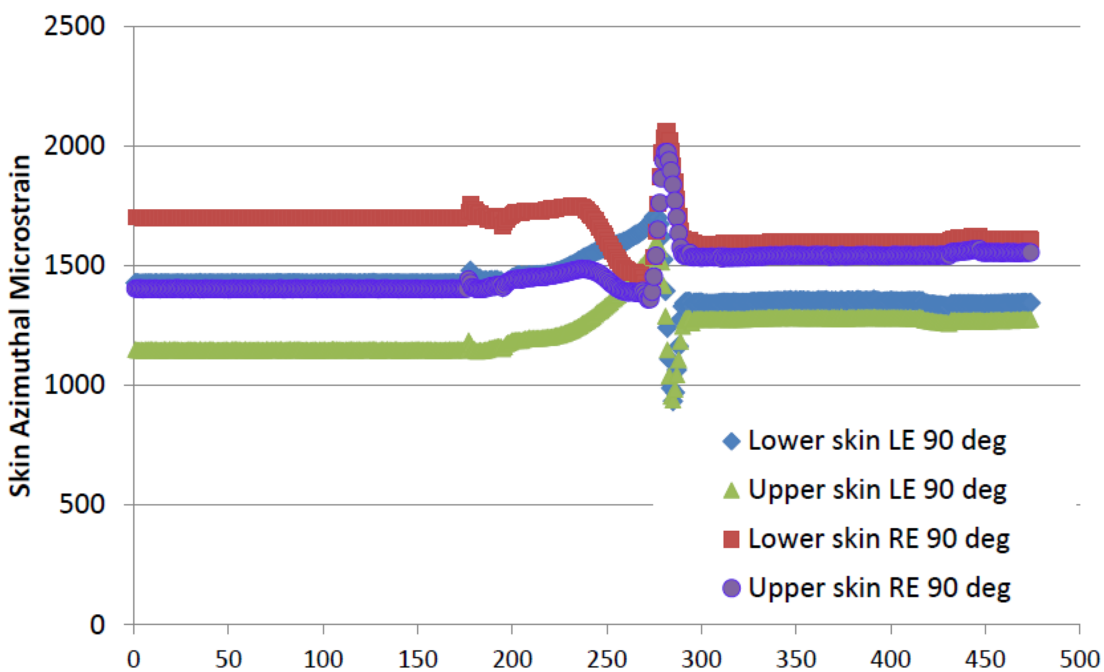

Fig 18 Skin gauges at 90 deg. during cool-down

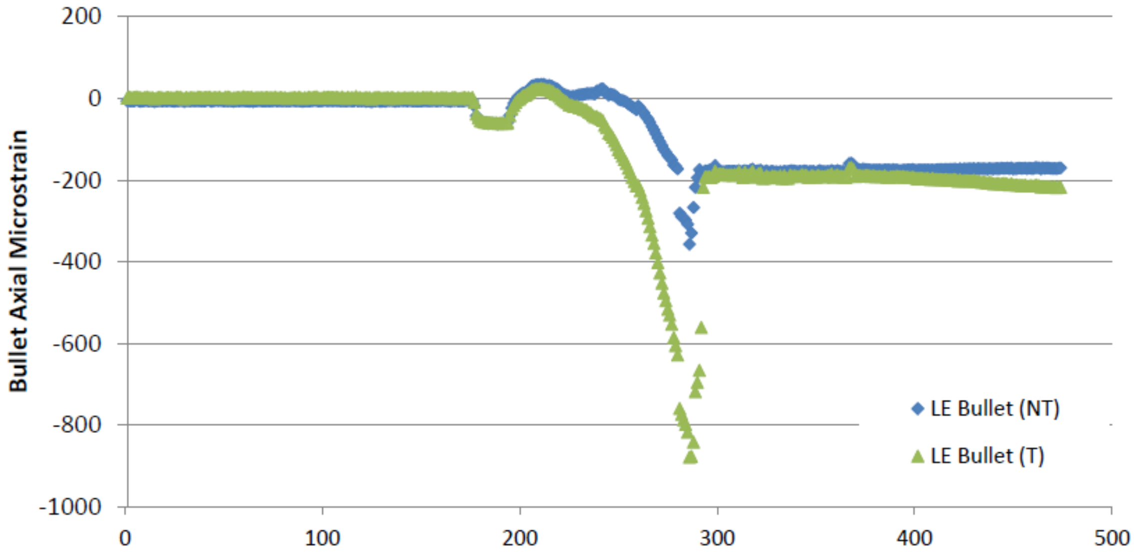

Fig 19 LE bullet gauges during cool-down

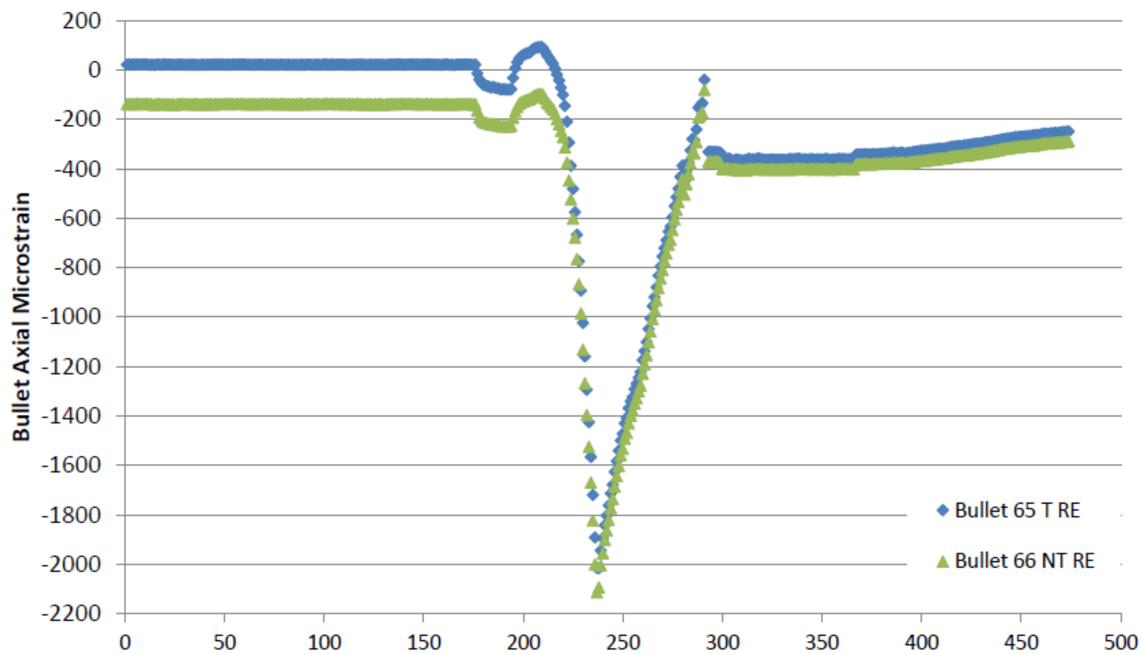

Fig 20 RE bullet gauges during cool-down

6.2 Excitation

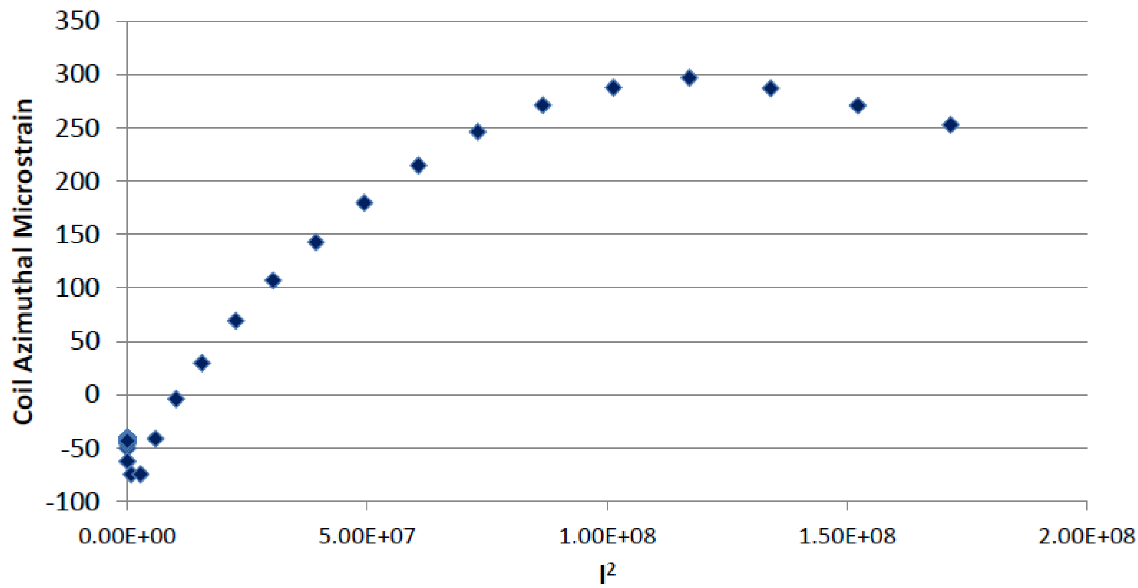

Fig 21 Azimuthal microstrain in the coil pole vs. I^2 (A^2) for quench 46 (14.6 kA)

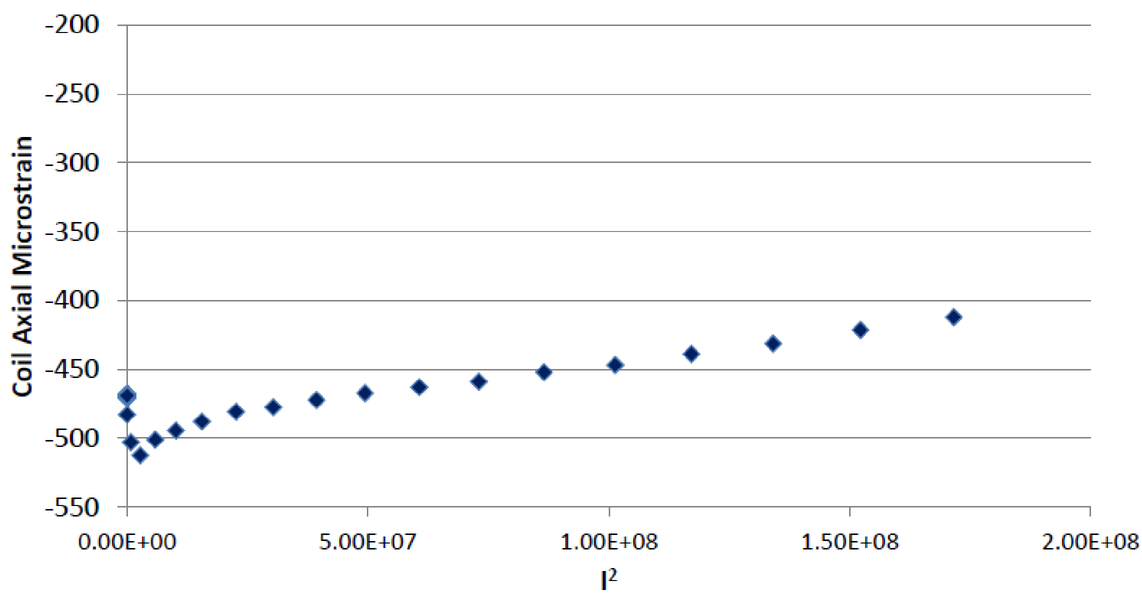

Fig 22 Axial microstrain in the coil pole vs. I^2 (A^2) for quench 46 (14.6 kA)

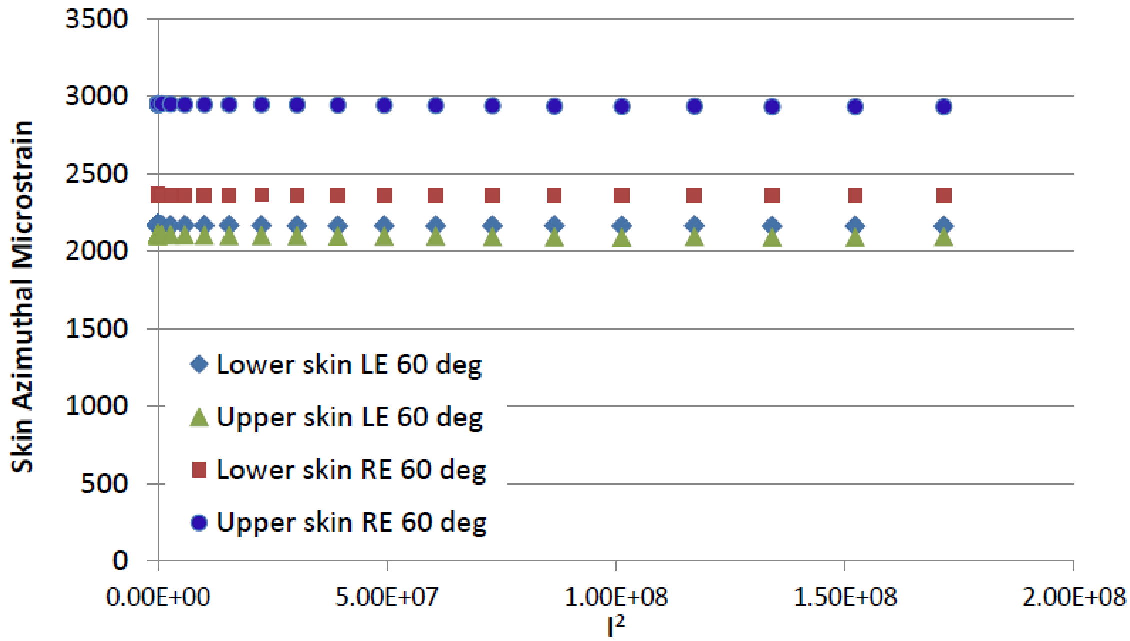

Fig 23 Skin azimuthal microstrain at 60 deg. vs. I^2 (A^2) for quench 46 (14.6 kA)

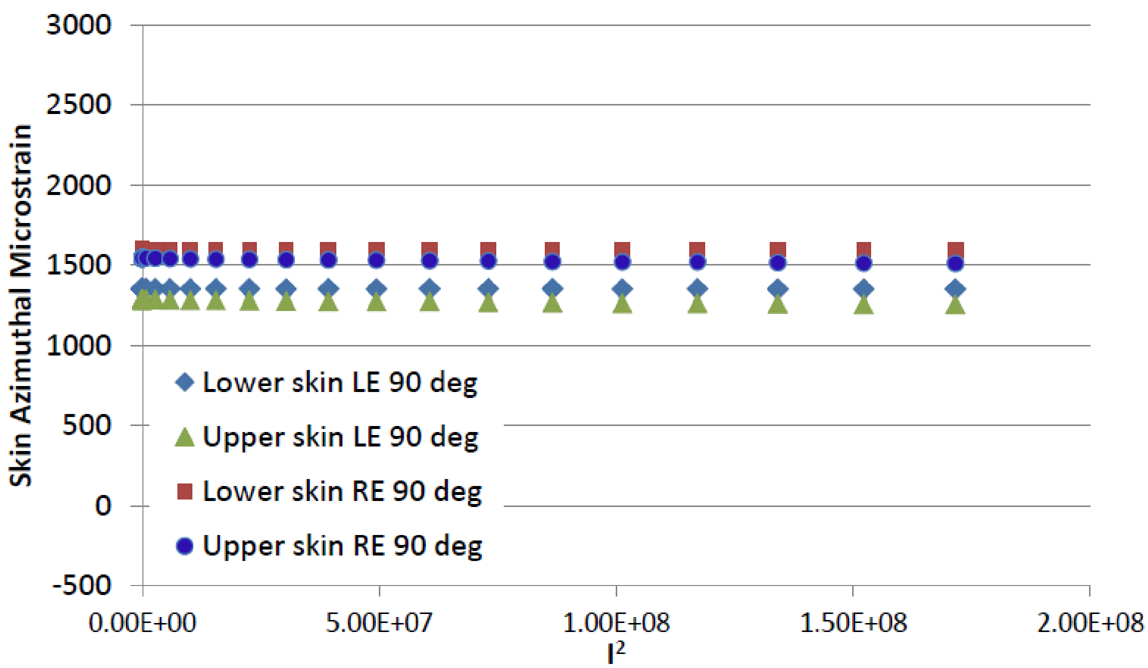

Fig 24 Skin azimuthal microstrain at 90 deg. vs. I^2 (A^2) for quench 46 (14.6 kA)

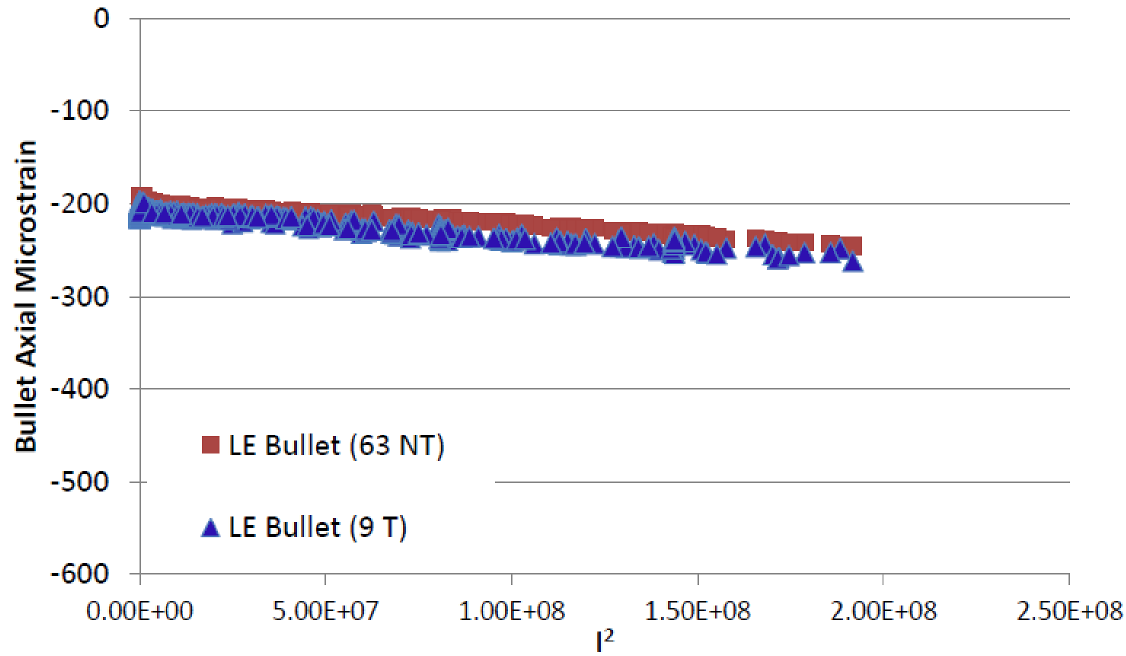

Fig 25 Axial microstrain in the LE bullets vs. I^2 (A^2) for quench 46 (14.6 kA)

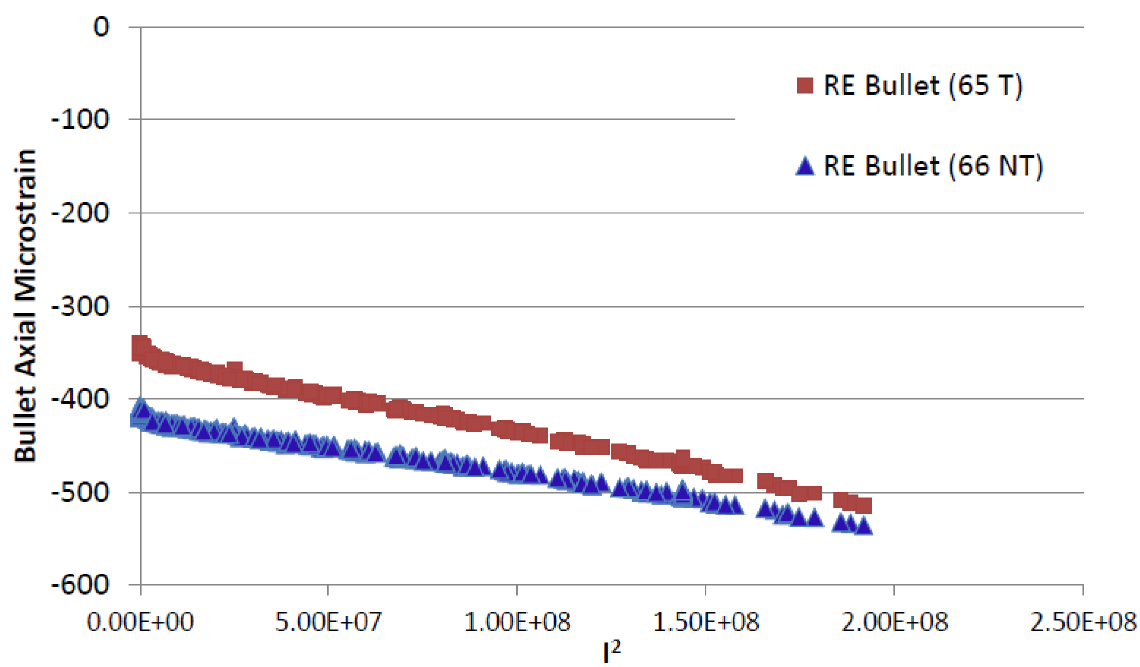

Fig 26 Axial microstrain in the RE bullets vs. I^2 (A^2) for quench 46 (14.6 kA)

6.3 Warm-up

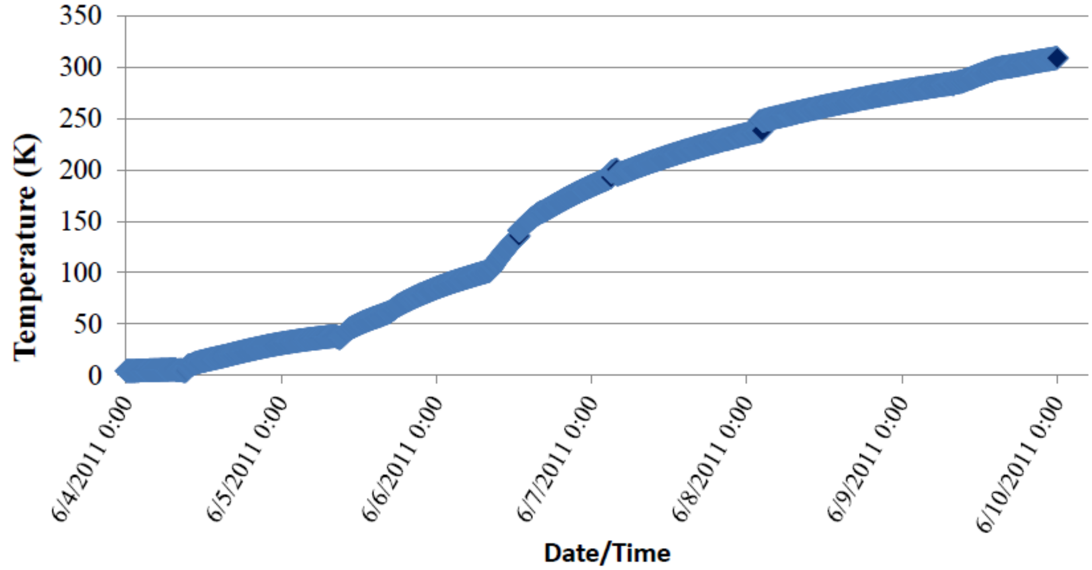

Fig. 27 Temperature of the magnet skin (top) measured during warm-up vs. time

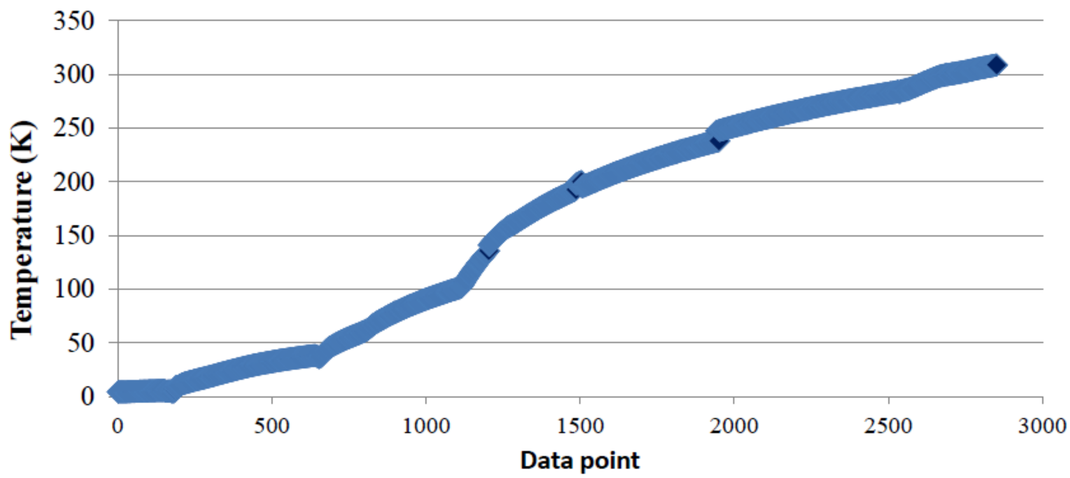

Fig. 28 Temperature of the magnet skin (top) measured during warm-up vs. data point

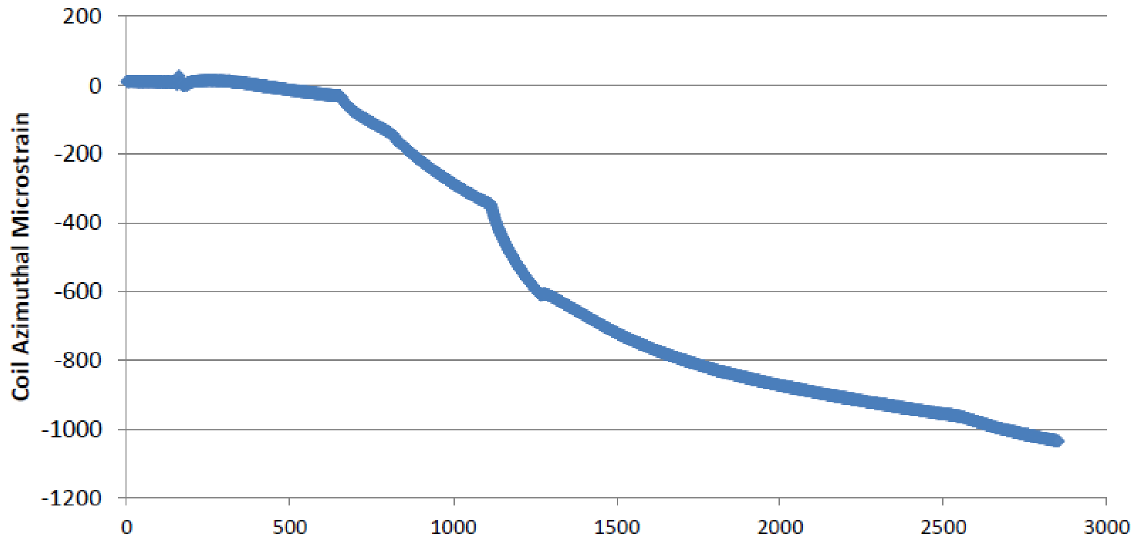

Fig 29 Azimuthal microstrain in the coil pole measured during warm-up

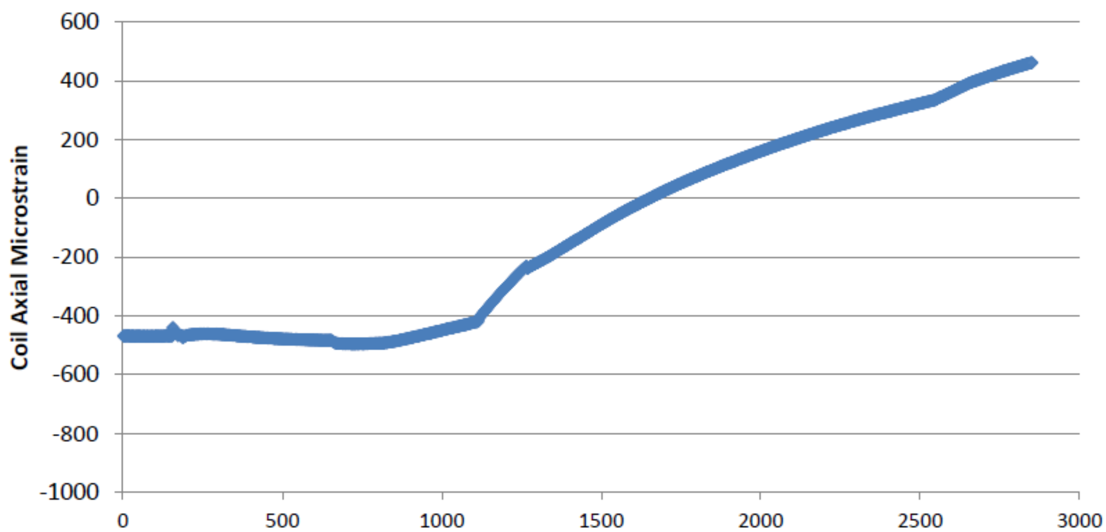

Fig 30 Axial microstrain in the coil pole measured during warm-up

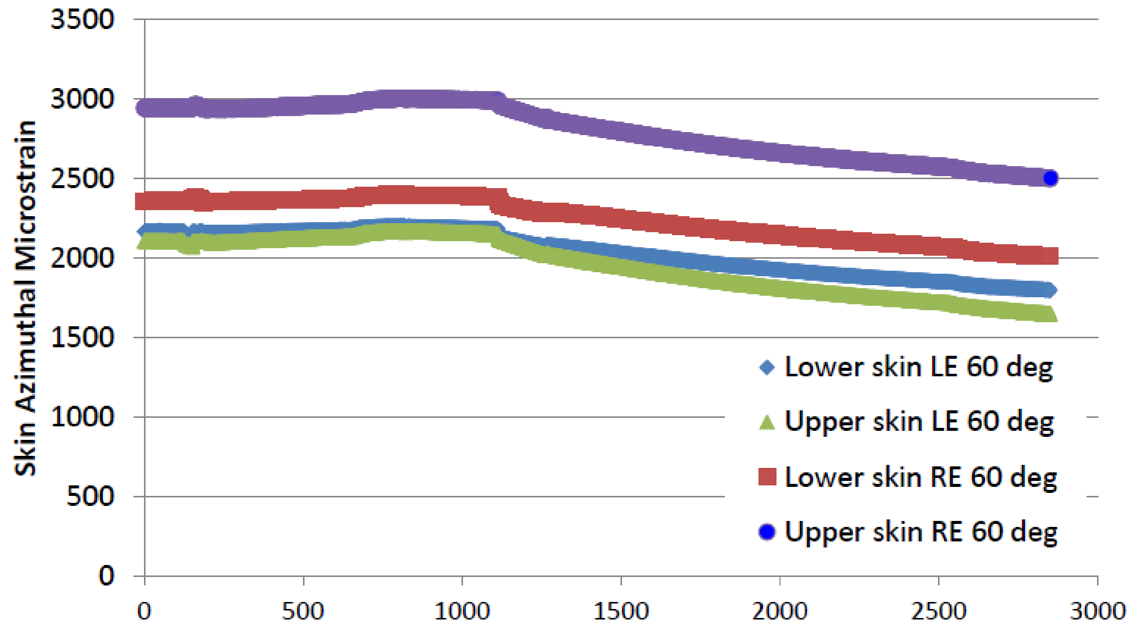

Fig 31 Skin gauges at 60 deg. during warm-up

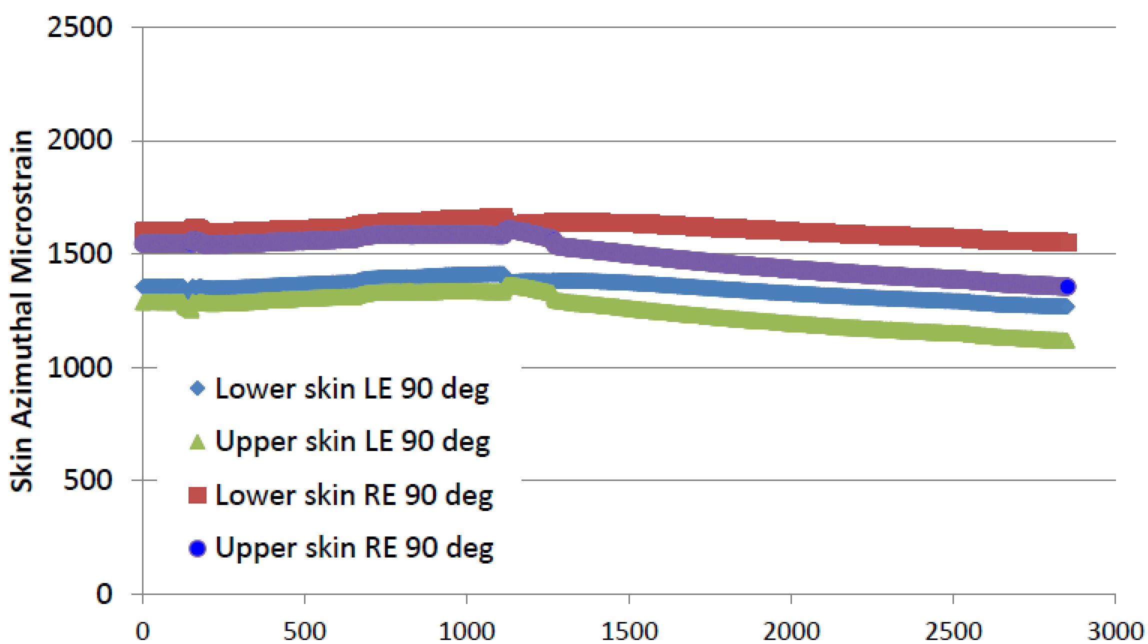

Fig 32 Skin gauges at 90 deg. during warm-up

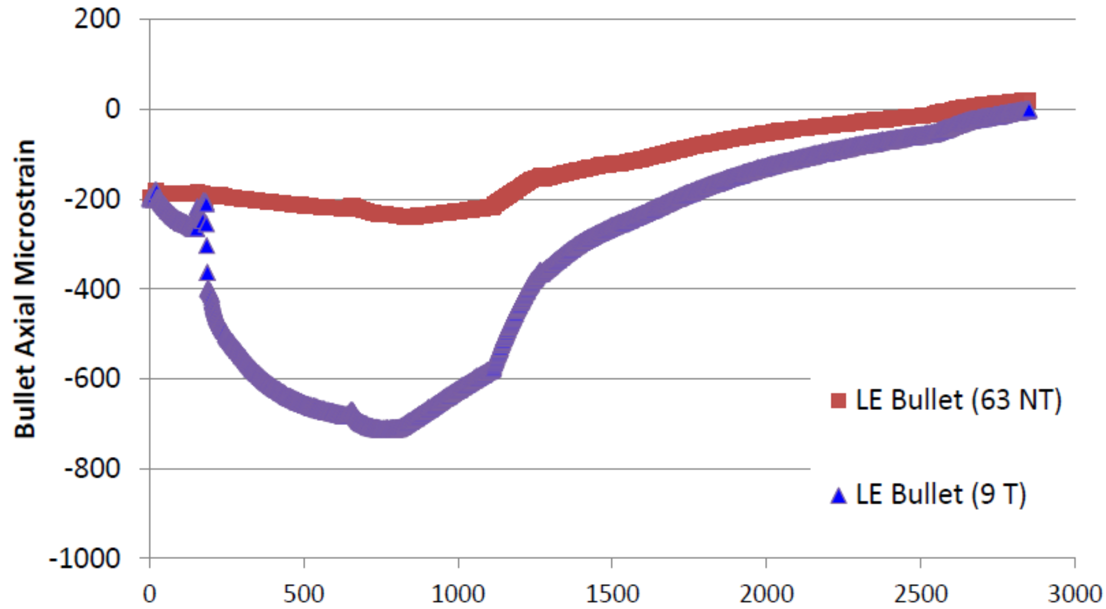

Fig 33 LE bullet gauges during warm-up

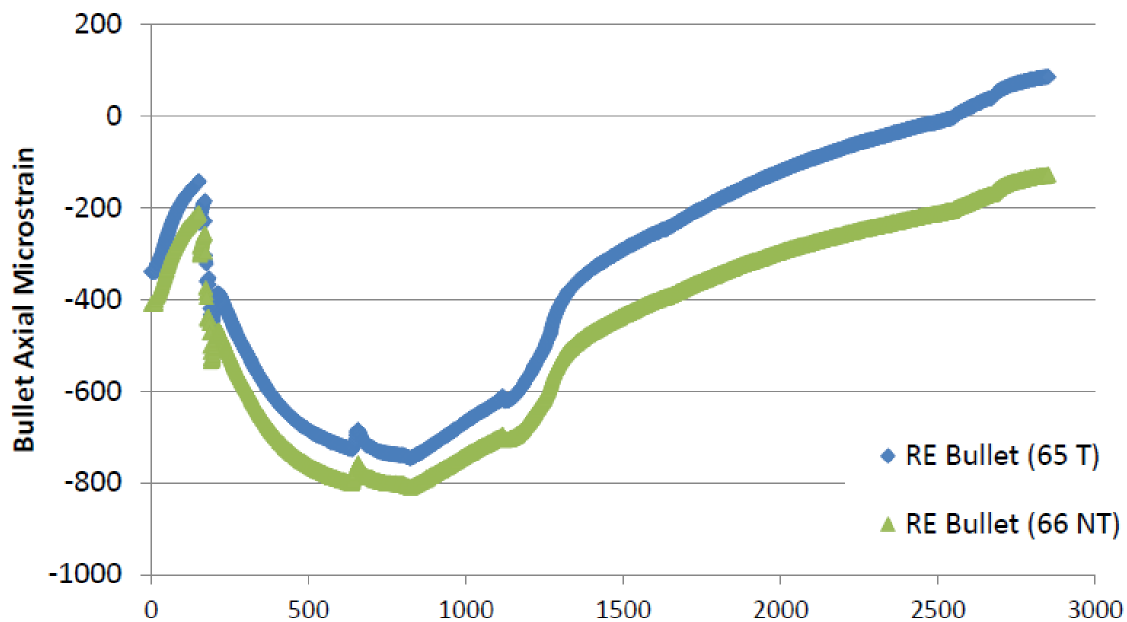

Fig 34 RE bullet gauges during warm-up

7 Protection Heater Study

Coil 13 was equipped with 25 µm thick stainless steel protection heaters. 2 heaters were placed both on the inner and outer coil surfaces, one on the transition side (i.e. inner to outer coil layer transition) and one on the non-transition side (denoted as ***T*** and ***NT*** in the table below). Heater resistances are listed in Table 3.

Table 3 Protection heater parameters in HQM01

PH	R at 300 K, Ohm	R at 4.6 K, Ohm	Area, cm2
INN (T)	6.47	4.75	217
INN (NT)	6.45	4.71	217
OUT (T)	6.05	4.42	243
OUT (NT)	6.01	4.37	243

Protection heater (PH) studies were done at 4.6 K. Only the outer layer non-transition (NT) heater was fired, while all other heaters were protecting the magnet. Quench delay (time delay from the heater firing time to the quench onset time) was measured at different capacitance and voltage of the heater firing unit (HFU). Quench delay as a function of the magnet current is shown in Fig. 35.

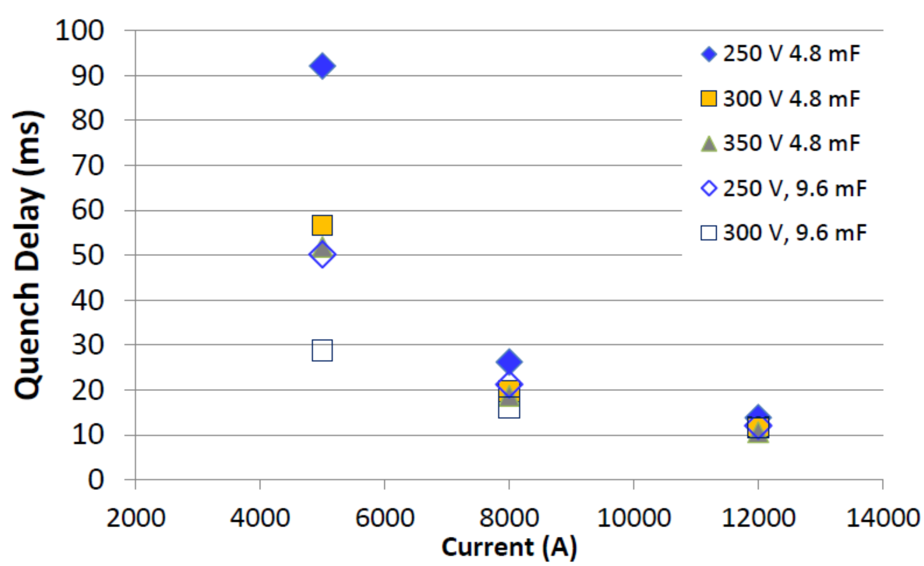

Fig 35 Quench delay as a function of magnet current

Quench delay is also shown as a function of the peak power density in the heater (see Fig. 36). One can see that quench delay is smaller when the magnet current is closer to the short sample limit. The quench delay also is getting smaller when the heater peak power density or time constant is increasing.

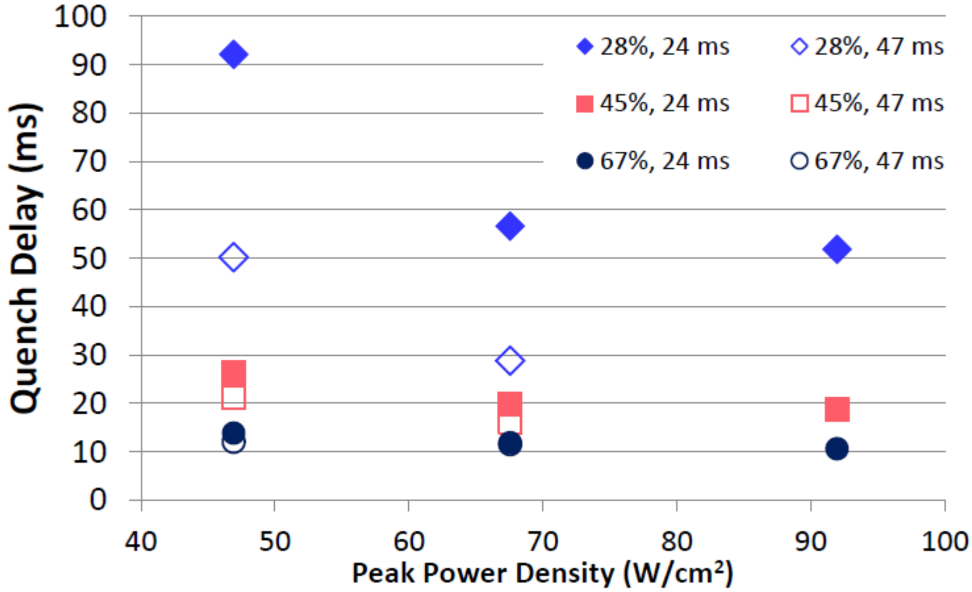

Fig 36 Quench current as a function of the PH peak power density (the percentage of short sample current and time constant for the heater current decay are also shown).

8 MIITs Study

A study aiming at evaluating the effects of high MIITs was performed at 4.6 K. The HQM01 coil was not equipped with a spot heater. Therefore spontaneous quenches were used during this study. In these quenches MIITs were allowed to increase by progressively delaying dump and (or) protection heaters. For MIITs study dump resistor was changed from 30 mΩ to 15 mΩ. Periodically, quenches with regular protection and dump delay settings were initiated to observe a possible degradation due to high MIITs. Quenches with a regular dump and PH delay were performed after quenches where accumulated MIITs reached 9, 14, 15, 16 and $17 \times 10^6 A^2s$. Standard dump and PH delay settings are shown in Table 4.

Table 4 Dump and PH delay settings for a regular training quench

Dump resistor	Dump delay	PH delay	HFU voltage
15 mOhm	1 ms	0 ms	200 V

In the first part of the test, the dump delay was increased from 1 ms to 120 ms with a heater delay of 0 ms and an average peak power density of 26 W/cm^2. For comparison, a few tests were done with an average peak power density of 82 W/cm^2. MIITs as a function of dump delay is shown in Fig. 37. Then the dump was removed by setting a very large delay of 1s. The heater delay was varied from 0 to 150 ms with an average peak power density of 82 W/cm^2. MIITs as a function of heater delay is shown in Fig. 38. Even without dump resistor and protection heaters (dump delay of 1s and heater delay >40 ms) the accumulated MIITs did not exceed $20.8 \times 10^6 A^2s$.

During 6 quenches the accumulated MIITs were exceeding $20\times10^6 A^2s$ without any degradation in HQM01 performance. It should be noted that HQM01 quenches were located in a low field area where a large margin exists. Therefore a large degradation (more than 46%) is necessary to be noticed in this location.

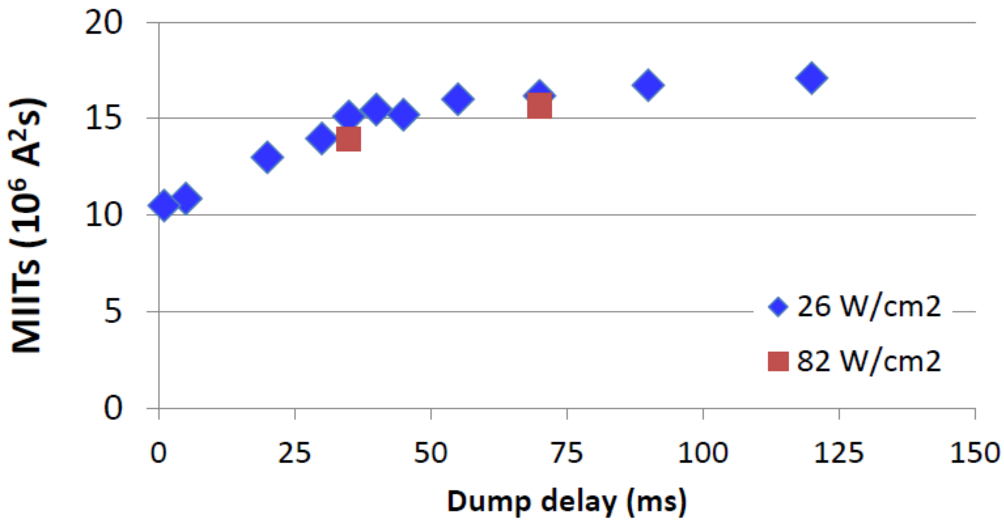

Fig. 37 MIITs as a function of dump delay.

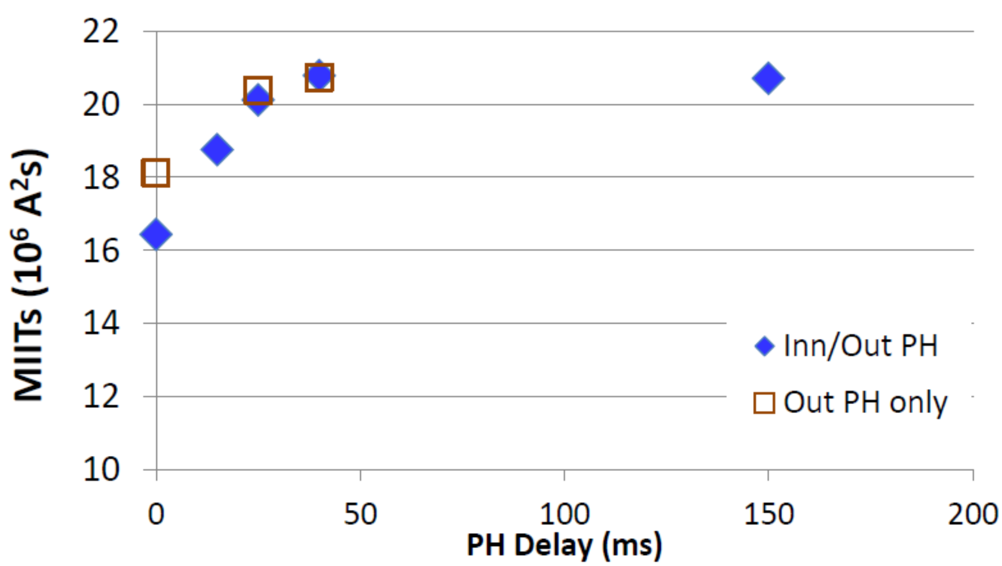

Fig. 38 MIITs as a function of heater delay.

9 Spike Data Analysis

The voltage spike detection system (VSDS) based on a National Instruments PXI multifunction DAQ was used to study thermo-magnetic instabilities in the HQM01 magnet. The VSDS captures half-coil signals at a sampling rate of 100 kHz. More details on this system are presented in [8]-[9].

The VSDS data was used for adjusting the quench detection thresholds. The number of voltage spikes and the maximum spike voltage as a function of the magnet current at 4.6 K are shown in Fig. 39. The largest amount of spikes is detected around 1000 A. The maximum voltage varies from 0.1 to 0.55 V. A two-peak structure in the spike distribution is caused by different ramp rates used during the quench training.

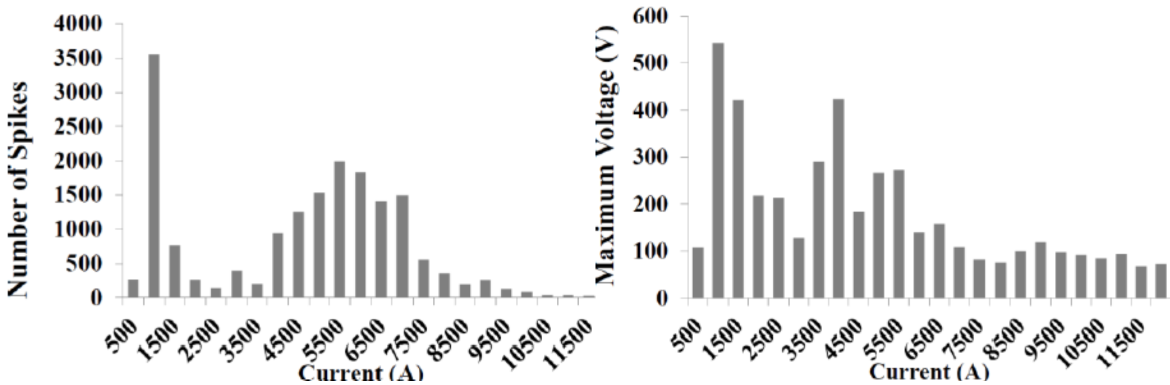

Fig. 39 Number of voltage spikes (left) and maximum voltage spike values (right) as a function of magnet current at 4.6 K

10. Summary

An HQ quadrupole coil with a 120-mm bore has been tested in a mirror structure. Reduced cable compaction and a cored configuration were being studied. Test results confirmed the efficiency of the SS core in suppressing eddy currents in the cable.

The coil reached only 82% of the critical current at 4.6 K and 77% at 2.2 K. Almost all quenches were initiated in the low field area near the inner layer mid-plane. The reason for quenching in the mid-plane area is unknown. Quenches in the mid-plane segment could be related to conductor damage resulting in a lower stability margin. The “reversed ramp rate dependence” could then be explained by the larger heat generated during faster ramp rates. Heat decreases the critical current of the conductor and therefore increases stability. Splice resistance was found reasonably small (0.2 – 0.3 nΩ) at both the inner and outer coil layer ends.

High-MIITs studies showed that both coil and structure manage to absorb all the stored energy at 82% of the magnet short sample limit.

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Attachment I